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Sustainable Futures in a Changing World – Reflections from the 5th International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters (ICSF 2024)

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Sustainable Futures in a Changing World – Reflections from the 5th International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters (ICSF 2024)

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Abstract. This paper presents an overview of the 5th International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters (ICSF 2024), held in May 2024. The conference brought together over 250 researchers, practitioners, and educators from 19 countries to share cutting-edge research and innovative solutions across a wide range of sustainability-related disciplines. The proceedings cover diverse topics, including climate change, disaster risk reduction, sustainable infrastructure, education for sustainability, environmental engineering, and sustainable business practices. Key themes that emerged include the integration of digital technologies in sustainability efforts, the impacts of global crises on sustainable development, and the importance of interdisciplinary approaches. The conference showcased both theoretical advancements and practical applications, with a particular focus on addressing the United Nations Sustainable Development Goals. This overview highlights the conference's role in fostering global dialogue and collaboration to address pressing sustainability challenges and shape a more sustainable future.

In memory of Serhii M. Chukharev, a brilliant researcher and dear friend.

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 2024, a symbol of our collective commitment to fostering sustainable futures.

Figure 1. ICSF 2024 logo (designed by Andrii M. Striuk).

Since its inception in 2020, ICSF has consistently 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 [1–5].

ICSF 2024 is a two-tiered platform comprising pre-conference workshops and the main conference, ensuring an enriched experience for all participants. The pre-conference workshops delve into specific domains of sustainable development.

1.1. Geography for Sustainable Development (GSD-2024)

Geography for Sustainable Development (GSD-2024) 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. Olha Bondarenko guides these explorations through her leadership.

Workshop URL: https://bondarenkoolga9.wixsite.com/gsd-2024.

1.2. Water for the Future: Management, Use, and Technology (WaterManEnvE-2024)

The *Water for the Future: Management, Use, and Technology* (WaterManEnvE-2024) stands as a peer-reviewed international platform, encapsulating contributions that cover all aspects of water management and environmental engineering, environmental education and modern 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-ws2024/home.

1.3. Nuclear Safety and Environmental Protection (IASEI-2024)

Nuclear Safety and Environmental Protection (IASEI-2024) 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 is in charge of cultivating innovative discussions.

Workshop URL: https://iasei.easyscience.education/2024/.

1.4. Infrastructure, Resilience and Sustainable Energy (SEnW-2024)

Infrastructure, Resilience and Sustainable Energy (SEnW-2024) 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 resilient future. Guided by Dr. Volodymyr Artemchuk, this workshop paves the way for sustainable energy practices.

Workshop URL: https://ipme.kiev.ua/en/SEnW-2024/.

1.5. Conference sessions

The main conference unfolded through a series of 12 sessions, each shedding light on different facets of sustainable development. These sessions encompassed topics ranging from sustainable mining, materials and technologies to socio-economic development, energy systems, water management, and beyond.

- Session 1. Sustainable mining. Geophysics, geology, mineralogy and petrology, session 1 (May 21, 2024). Chairs: Serhii Chukharev and Andrii Striuk
- Session 2. Technology and materials for sustainability (May 21, 2024). Chair: Serhiy Sakhno
- Session 3. Infrastructure, Resilience and Sustainable Energy (SEnW-2024) (May 21, 2024). Chair: Volodymyr Artemchuk

Session 4. Sustainable use of natural resources. Sustainable transportation (May 21, 2024). Chair: Pavlo Nechypurenko

Session 5. Geography for a Sustainable Future (GSD-2024), session 1 (May 21, 2024). Chair: Olha Bondarenko

Session 6. Green building and sustainable architecture. Sustainable urban planning, cities and society (May 22, 2024). Chair: Serhiy Sakhno

Session 7. Education for sustainability (May 22, 2024). Chair: Tetiana Vakaliuk

Session 8. Sustainable business practices. Environmental policy, economics, and law. Environmental health and sustainable development (May 22, 2024). Chair: Hanna Danylchuk

Session 9. Water for the Future: Management, Use, and Technology (WaterManEnvE-2024) (May 22, 2024). Chair: Serhii Klimov

Session 10. Nuclear Safety and Environmental Protection (IASEI-2024) (May 23, 2024). Chairs: Valeriia Kovach, Andrii Iatsyshyn and Teodoziia Yatsyshyn

Session 11. Sustainable mining. Geophysics, geology, mineralogy and petrology, session 2 (May 23, 2024). Chair: Serhii Chukharev and Andrii Striuk

Session 12. Geography for a Sustainable Future (GSD-2024), session 2 (May 24, 2024). Chair: Olha Bondarenko

This volume is a repository of the scholarly contributions presented at ICSF 2024. 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, and perspective/colloquia articles on conference topics of interest (`https://www.morressier.com/call-for-papers/6501c5b1cd3f7d001924450d`). With meticulous reviews conducted by a minimum of three program committee members, the selected papers embody the spirit of rigorous exploration and discovery. Out of 304 submissions received, 171 papers were accepted after a rigorous peer-review process.

The unfolding events of the ongoing Russian invasion of Ukraine necessitated a hybrid conference format. By embracing both in-person and online modes, ICSF 2024 extended its reach across borders, allowing more than 250 participants from 19 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,
- other talks (15 min): 10 min presentation and 5 minutes question answering and discussion.

The full ICSF 2024 program is available at the `https://icsf.easyscience.education/2024/`, where one or more invited presentations usually head details of the sessions. Video records of talks are available at the *Not So Easy Science* YouTube channel:

`https://www.youtube.com/channel/UCH3gego79m-ofCiNEgEzMuA`

As we present these proceedings, we invite readers to explore the diverse range of topics covered, draw inspiration from the innovative approaches discussed, and consider how these findings can be applied to enhance sustainable practices across various contexts and disciplines. We anticipate that the ideas and findings presented will significantly contribute to shaping a more sustainable future.

2. ICSF 2024 program committee

The ICSF 2024 program committee comprised over 100 distinguished researchers from around the world, representing a wide range of disciplines related to sustainable development. Their expertise and dedication were instrumental in ensuring the high quality of the papers presented at the conference.

- *Leon A. Abdillah*, Universitas Bina Darma, Indonesia [6, 7]
- *Khairulla Aben*, CSA Global, Australia [8, 9]
- *George Abuselidze*, Batumi Shota Rustaveli State University, Georgia [10]
- *Rajendran Sobha Ajin*, University of Florence, Italy [11–15]
- *Tetiana Alokhina*, Kryvyi Rih State Pedagogical University, Ukraine [16–19]
- *Volodymyr Artemchuk*, G. E. Pukhov Institute for Modelling in Energy Engineering of NAS of Ukraine, Ukraine [20–26]
- *Jozef Bendík*, Slovak University of Technology in Bratislava, Slovakia [27–29]
- *Milan Bělík*, University of West Bohemia, Czechia [30–34]
- *Tetiana Bilan*, State Scientific and Technical Center for Nuclear & Radiation Safety, Ukraine [35–37]
- *Ihor Blinov*, Institute of Electrodynamics of the National Academy of Sciences of Ukraine, Ukraine [38, 39]
- *Olha Bondarenko*, Kryvyi Rih State Pedagogical University, Ukraine [40–47]
- *Liudmyla Burman*, Kryvyi Rih State Pedagogical University, Ukraine [48–51]
- *Matej Cenký*, Slovak University of Technology in Bratislava, Slovakia [52–54]
- *Serhii Chukhariev*, National University of Water and Environmental Engineering, Ukraine [55–59]
- *Giuseppe T. Cirella*, University of Gdansk, Poland [60–63]
- *Hanna Danylchuk*, The Bohdan Khmelnytsky National University of Cherkasy, Ukraine [64–69]
- *Iryna Davydova*, Zhytomyr Polytechnic State University, Ukraine [70–74]
- *Kremena Dedelyanova*, Scientific and technical union of mining, geology and metallurgy in Bulgaria, Bulgaria [75, 76]
- *Viktor Denysenko*, The Bohdan Khmelnytsky National University of Cherkasy, Ukraine [77–82]
- *Tetiana Derkach*, Kyiv National University of Technologies and Design, Ukraine [83–87]
- *Viktoriia Dmytrenko*, National University "Yuri Kondratyuk Poltava Polytechnic", Ukraine [88–91]
- *Iryna Dubovkina*, Institute of Engineering Thermophysics of NAS of Ukraine, Ukraine [92,93]
- *Oleksandr Farrakhov*, Center for Information-analytical and Technical Support of Nuclear Power Facilities Monitoring of the NAS of Ukraine, Ukraine [94–97]
- *Branko Gluščević*, University of Belgrade, Serbia [98–101]
- *Volodymyr Grinchenko*, General Energy Institute of the NAS of Ukraine, Ukraine [102–105]
- *Olena Hanchuk*, Kryvyi Rih State Pedagogical University, Ukraine [106–109]
- *Hermann Heilmeier*, Technische Universität Bergakademie Freiberg, Germany [110–113]
- *Serhii Honchar*, G. E. Pukhov Institute for Modelling in Energy Engineering of NAS of Ukraine, Ukraine [114–118]

- *Teodora Vassileva Hristova*, University of mining and geology “St. Ivan Rilski”, Bulgaria [119, 120]
- *Pavlo Hryhoruk*, Khmelnytskyi National University, Ukraine [121–125]
- *Andrii Iatsyshyn*, Center for Information-analytical and Technical Support of Nuclear Power Facilities Monitoring of the NAS of Ukraine, Ukraine [126–130]
- *Anna Iatsyshyn*, State Scientific Organization “Ukrainian Institute of Scientific Technical and Expertise and Information”, Ukraine [131–134]
- *Nataliia Ivanenko*, Institute of General Energy of the NAS of Ukraine, Ukraine [135–138]
- *Mykola Kharytonov*, Dnipro State Agrarian and Economic University, Ukraine [139]
- *Ihor Kholoshyn*, Kryvyi Rih State Pedagogical University, Ukraine [140–142]
- *Liubov Kibalnyk*, The Bohdan Khmelnytsky National University of Cherkasy, Ukraine [143–146]
- *Arnold Kiv*, Ben-Gurion University of the Negev, Israel [147]
- *Serhii Klimov*, National University of Water and Environmental Engineering, Ukraine [148–153]
- *Elena Komarova*, NitrosData, LLC [154–156]
- *Valerii Korniyenko*, National University of Water and Environmental Engineering, Ukraine [157–160]
- *Valeriia Kovach*, Center for Information-analytical and Technical Support of Nuclear Power Facilities Monitoring of the NAS of Ukraine, Ukraine [161–164]
- *Oksana Kovtun*, University of Educational Management [165–168]
- *Andrey Kupin*, Kryvyi Rih National University, Ukraine [169–172]
- *Olena Kuzminska*, National University of Life and Environmental Sciences of Ukraine, Ukraine [173–176]
- *Evgeniy Lavrov*, Sumy State University, Ukraine [177–181]
- *Olena Lavrova-Manzenko*, The Bohdan Khmelnytsky National University of Cherkasy, Ukraine [182]
- *Tetiana Lazarieva*, Ukrainian Engineering Pedagogics Academy, Ukraine [183–185]
- *Cristina Leonelli*, University of Modena and Reggio Emilia, Italy [186–188]
- *Nadiia Lobanchykova*, Zhytomyr Polytechnic State University, Ukraine [189–193]
- *Oleh Lysak*, Institute of Renewable Energy of the National Academy of Sciences of Ukraine, Ukraine [194–196]
- *Nataliia Maksyshko*, Zaporizhzhia National University, Ukraine [197–201]
- *Svitlana Malchenko*, Kryvyi Rih State Pedagogical University, Ukraine [202–205]
- *Anatolii Matsui*, Central Ukrainian National Technical University, Ukraine [206–208]
- *Oleksii Merkulov*, Iron and Steel Institute of Z.I. Nekrasov of NAS of Ukraine, Ukraine [209]
- *Bård Borch Michalsen*, UiT The Arctic University of Norway, Norway [210]
- *Iryna Mintii*, Kryvyi Rih State Pedagogical University, Ukraine [211]
- *Roland Iosif Moraru*, University of Petrosani, Romania [212–214]
- *Victor Mutambo*, University of Zambia, Zambia [215–218]
- *Oleksii Mykhailenko*, Kryvyi Rih National University, Ukraine [219–221]
- *Tetiana Nazarenko*, Institute of Pedagogy of the National Academy of Educational Sciences of Ukraine, Ukraine [222, 223]

- *Pavlo Nechypurenko*, Kryvyi Rih State Pedagogical University, Ukraine [224–230]
- *Borya Orkhontuul*, Mongolian University of Science and Technology, Mongolia [231]
- *Kateryna Osadcha*, Norwegian University of Science and Technology, Norway [232–235]
- *Viacheslav Osadchyi*, Borys Grinchenko Metropolitan Kyiv University, Ukraine [236–240]
- *Marinela Ivanova Panayotova*, University of Mining and Geology "St. Ivan Rilski", Bulgaria [241–245]
- *Natalia Panteleeva*, Kryvyi Rih State Pedagogical University, Ukraine [246–249]
- *Andrii Peremetchyk*, Kryvyi Rih National University, Ukraine [250–253]
- *Mykhailo Petlovanyi*, Dnipro University of Technology, Ukraine [254–257]
- *Olha Pinchuk*, Institute of Information Technologies and Learning Tools of the NAES of Ukraine, Ukraine [258]
- *Oleksandr Popov*, Center for Information-analytical and Technical Support of Nuclear Power Facilities Monitoring of the NAS of Ukraine, Ukraine [259–261]
- *Vasyl Porokhnya*, Classic Private University, Ukraine [262–266]
- *Oleg Pursky*, Kyiv National University of Trade and Economics, Ukraine [267–269]
- *Olena Remezova*, Institute of Geological Sciences of the National Academy of Sciences of Ukraine [270–274]
- *Olena Rubanenko*, Vinnitsa National Technical University, Ukraine [275–277]
- *Ivan Sakhno*, Donetsk National Technical University, Ukraine [278–281]
- *Serhiy Sakhno*, Kryvyi Rih National University, Ukraine [282–284]
- *Myroslav Sanytsky*, Lviv Polytechnic National University, Ukraine [285, 286]
- *Tetiana Selivanova*, Kryvyi Rih State Pedagogical University, Ukraine [287–289]
- *Serhiy Semerikov*, Kryvyi Rih State Pedagogical University, Ukraine [290–292]
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- *Sergii Skurativskyi*, Institute of Geophysics National Academy of Sciences of Ukraine, Ukraine [311–313]
- *Valentyna Stanytsina*, Institute of general energy of NAS of Ukraine, Ukraine [314–318]
- *Andrii Striuk*, Kryvyi Rih National University, Ukraine [319–322]
- *Izabela Barbara Sztangret*, University of Economics in Katowice, Poland [323–327]
- *Radomir Timchenko*, Kryvyi Rih National University, Ukraine [328–330]
- *Mihaela Toderaș*, University of Petrosani, Romania [331–333]
- *Krzysztof Marian Tomiczek*, Silesian University of Technology, Poland [334–337]
- *Vitalii Tron*, Kryvyi Rih National University, Ukraine [338–341]
- *Iryna Trubavina*, Kryvyi Rih State Pedagogical University, Ukraine [342–344]
- *Illia Tsyhanenko-Dziubenko*, Zhytomyr Polytechnic State University, Ukraine [345–347]
- *Tetiana Vakaliuk*, Zhytomyr Polytechnic State University, Ukraine [348–353]
- *Iryna Varfolomyeyeva*, Kryvyi Rih State Pedagogical University, Ukraine [354–356]

- *Kateryna Vlasenko*, National University of Kyiv-Mohyla Academy, Ukraine [357–361]
- *Yuriy Vynnykov*, National University “Yuri Kondratyuk Poltava Polytechnic”, Ukraine [362–366]
- *Petro Vyshnivskyi*, National University of Life and Environmental Sciences of Ukraine, Ukraine [367, 368]
- *Teodoziia Yatsyshyn*, Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine [369–372]
- *Nataliia Zachosova*, The Bohdan Khmelnytsky National University of Cherkasy, Ukraine [373–377]
- *Ievgen Zaitsev*, The Institute of Electrodynamics of the National Academy of Sciences of Ukraine [378–382]
- *Oleksandr Zgurovets*, Institute of General Energy of NAS of Ukraine, Ukraine [383–386]
- *Iryna Zinovieva*, Kyiv National Economic University named after Vadym Hetman, Ukraine [387–391]
- *Valerij Zvaritch*, Institute of Electrodynamics of the National Academy of Sciences of Ukraine, Ukraine [392–395]

3. ICSF 2024 organizer

The 5th edition of ICSF was meticulously coordinated by the Academy of Cognitive and Natural Sciences (ACNS, `https://acnsci.org`), 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.
- Orchestrating conferences, workshops, training sessions, internships, and other platforms for the exchange and dissemination of knowledge in the realm of cognitive and natural sciences.
- 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 of Edge Computing* (JEC) that covers a broad range of topics aligned with the Sustainable Development Goals (SDGs). Here are select articles from *Journal of Edge Computing* categorized by SDG goals:

SDG 3 (Good Health and Wellbeing)

- Non-contact photoplethysmographic sensors for monitoring students' cardiovascular system functional state in an IoT system [396].
- Model of an automated biotechnical system for analyzing pulseograms as a kind of edge devices [397].
- A system for monitoring the microclimate parameters of premises based on the Internet of Things and edge devices [398].
- An IoT system based on open APIs and geolocation for the prevention of human health disorders [399].
- Responding to challenge call for machine learning model development in diagnosing respiratory disease sounds [400].

SDG 4 (Quality Education)

- Design and implementation of an IoT-based educational model for smart homes: a STEM approach [401].
- Investigating the effect of virtual machine migration accounting on reliability using a cluster model [402].

SDG 9 (Industry, Innovation, and Infrastructure)

- Graph theory methods for fog computing: A pseudo-random task graph model for evaluating mobile cloud, fog and edge computing systems [403].
- Analysis and protection of IoT systems: Edge computing and decentralized decision-making [404].
- A new approach for dispatching task flows in GRID systems with inalienable resources [405].
- Introduction to doors Workshops on Edge Computing (2021-2023) [406].
- ImpalaE: Towards an optimal policy for efficient resource management at the edge [407].
- Reliable distributed systems: review of modern approaches [408].
- Empowering the Edge: Research advances from doors 2024 [409].
- Efficient model of PID controller of unmanned aerial vehicle [410].
- Design and implementation of an edge computing-based GPS tracking system [411].
- Telemetry to solve dynamic analysis of a distributed system [412].
- Advancing IoT interoperability: dynamic data serialization using ThingsBoard [413].
- Ambience: an operating system for IoT microservices [414].
- Use of wireless technologies in IoT projects [415].

SDG 11 (Sustainable Cities and Communities)

- Edge computing in environmental science: automated intelligent robotic platform for water quality assessment [416].

SDG 15 (Life on Land)

- Enhanced deep learning model architecture for plant disease detection in Chilli plants [417].

SDG 16 (Peace, Justice, and Strong Institutions)

- A long short-term memory based approach for detecting cyber attacks in IoT using CIC-IoT2023 dataset [418].

4. Proceedings structure

4.1. Atmospheric science, meteorology, and climatology

The papers in this section cover topics related to atmospheric science, meteorology, and climatology. [419] investigates methane degassing within Ukraine using satellite data. [420] analyzes patterns of PM10 particles change in the atmospheric air of Ivano-Frankivsk city. [421] explores the application of remote monitoring tools in the educational process by studying the content of water vapour in the atmosphere. [422] explores the use of FEM technology in analyzing the stability of the design concept of a residential building “Flower of Life” under explosive load conditions.

4.2. Biodiversity conservation and environmental impact

[423] assesses below-ground carbon stock of mangrove stands at a mining site in Hinatuan Island, Philippines. [424] investigates the accumulation of heavy metals by different biota representatives in the operation zone of the Prydniprovska thermal power plant. [425] proposes spatial optimization models of socio-natural interaction as a way to sustainable development.

4.3. Climate change, disaster risk reduction, and environmental policy

Climate change and its impacts are addressed in [426], which proposes ML-ERV, a machine learning-based CO_2 emissions model for rental vehicles. Disaster risk reduction is the focus of [427], a hermeneutic phenomenological study of motivations, challenges, and resilience in a landslide-prone environment in the Philippines. [428] assesses seismic hazard in the Shamkir-Mingachevir reservoir region through ground response analysis. Environmental policy is represented by [429], which explores stakeholders' awareness and perception of bio-economic transformation in Ukraine. [430] evaluates green flood mitigation measures in urban areas within the sustainable city concept. [431] investigates the physical and mechanical properties of burnt-out coal mine waste heaps. [432] assesses the risks for Ukraine's infrastructure under war conditions. [433] focuses on the resilience of systems for public protective actions under wartime.

4.4. Education for sustainability

Several papers address education for sustainability from various angles. [434] models the digital ecophilic tendencies of university students' consciousness. [435] explores the use of digital technologies in education in the context of sustainable development. [436] discusses inclusive culture in Ukrainian higher education institutions for sustainable development. [437] focuses on nanoeducation for a sustainable future and attracting Ukrainian youth to nanotechnological specialities. [438] investigates collaborative learning in training future IT specialists as a strategy for sustainable education. [439] explores transforming education and navigating the human-AI ecosystem in psychological training and beyond. [440] discusses ensuring sustainable development through digital educational hubs for teaching civic education at school. [441] presents a case study of students and plagiarism, focusing on plagiarism checker use at a university in North Sumatra. [442] investigates cultivating intercultural competency and the role of sustainability in pre-service teacher professional development. [443] provides a literature review on the educational dimension of sustainable development from 2019-2023. [444] explores the intersection of artificial intelligence, the labour market, and education for sustainable development. [445] explores the use of ICT by teachers for developing students' critical thinking in the context of sustainable development in Ukraine. [446] investigates transformational leadership in higher education for implementing sustainable development goals, using Ukraine as an example. [447] presents a case study of a school preparing for sustainability management, focusing on the Palau simulation model. [448] explores blended learning, its definition, concept, and relevance to education for sustainability. [449] proposes AI tools for sustainable primary teacher education, focusing on literary-artistic content generation.

4.5. Environmental engineering and green technology

Several papers represent environmental engineering and green technology. [450] evaluates green flood mitigation measures in urban areas within the sustainable city concept. [451] investigates increasing biogas production energy efficiency through vibration activation of heat and mass exchange in the bioreactor. [452] focuses on sustainability and resilience, exploring digital technologies for GHG Scope 3. [453] presents a geoinformation assessment of solar plant potential in the Ivano-Frankivsk region for effective decarbonisation and energy stability. [454] uses canonical correlations to assess the relationship between economic growth and environmental threats. [455] forecasts the development of the circular economy in Ukraine. [456] improves municipal wastewater treatment technology in towns and villages. [457] explores the prospects of using composite preparations based on silica nanosols. [458] provides a review of the current state and prospects of red mud utilization. [459] proposes technological solutions for the population under existing challenges.

4.6. Sustainable infrastructure, mining, transportation, and urban planning
Sustainable infrastructure is the focus of [460], which explores the automated trolleybus park system as part of sustainable city infrastructure. [461] proposes neural network methods for searching additional functions in information-driven permutation operations to increase critical infrastructure sustainability. Sustainable mining is represented by [462], considering multifactorial geomechanical-technological factors in determining rational parameters for site outgassing technology in Western Donbas mines, Ukraine. [463] models the soil erosion process during amber mining. [464] investigates the influence of stress-strain evolution in the immediate floor before and after excavation face on floor heave origin in coal mines roadways. Sustainable transportation is addressed by [465], analyzing prospects and peculiarities of autonomous and cyber-physical systems development for vehicle control at mining enterprises. [466] proposes a strategic approach to sustainable railway transport development and optimizing empty car use in organizing dangerous goods transportation. [467] presents a flight situation advisory system for uninterrupted and efficient air transportation. Sustainable urban planning is the focus of [468], which applies geoinformation systems in developing a city's intelligent transport network. [469] discusses problems in developing urban planning solutions for the restoration of deoccupied cities in eastern Ukraine. [470] explores the sustainable development of the Pirnovo community in the Kyiv region, focusing on problems and perspectives. [471] reviews smart city trends, achievements, and challenges in Ukraine in the context of Sustainable Development Goals. [472] applies geometrization to estimate mineral deposit reserves. [473] investigates the degree indicators of coal metamorphism for predicting hazardous properties of coal seams during mining. [474] explores predictive calculation of blasting quality as a tool for estimating production cost and investment attractiveness of mineral deposit development. [475] proposes a tool for management and planning of the fuel and energy complex, considering the production potential of coal-mining enterprises. [476] investigates the management of resource potential in European countries in the context of "post-coal mining". [477] researches the selection of optimal instrumentation for mine surveying and software for processing field results. [478] presents a methodology for the operative setting of mass crystallization parameters of gas hydrate in reservoir systems. [479] proposes an integrated approach to forecasting and managing emergencies in the working faces of coal mines, focusing on technical, organizational, and safety measures with subsequent assessment of potential consequences. [480] explores the application of prefabricated retaining walls with increased shear resistance to ensure tailings dam stability. [481] develops a method for estimating the carbon footprint when transporting grain by road. [482] predicts CO_2 emissions during multimodal grain transportation. [483] proposes an improvement technique for surveying observations of displacement. [484] analyzes quantitative and qualitative parameters of the gas mixture in thermal processes of mine medium. [485] applies GIS in the retrospective analysis of the territorial organization of the Kryvyi Rih settlement. [486] explores the geography of the COVID-19 pandemic in Ukraine and the world, focusing on similarities and differences. [487] investigates the features of functional zoning of esports arenas, considering the concepts of sustainable development of territories. [488] proposes the FUTURE 5.0 multi-goal decision-making framework for sustainable university governance in the Industry 5.0 era and beyond.

4.7. Agriculture, food systems, and natural resources
Several papers represent sustainable agriculture and food systems. [489] proposes a resource-saving method for extracting cucumber and melon seeds. [490] conducts experimental research on spray opening and closing time in flat and injector nozzles. [491] explores areas of nature reserve fund used in the context of sustainable development. [492] investigates consumer perceptions and determinants of millet milk consumption as a sustainable choice. Natural resources are the focus of [493], assessing changes in forest ecosystem structure using the example of sanitary

woody plantations in the Steppe Dnipro. [494] generates a geospatial database of forest growth using the QGIS software package. [495] explores the peculiarities of using statistical data for the mass valuation of agricultural lands in Ukraine, focusing on the Kharkiv region. [496] investigates the structural and functional content of xerophytic plants of the *Elytrigia repens L.* genus. [497] assesses trends in the functioning of the grain industry of EU countries using ARDL modelling. [498] explores the application of polymer flooding to increase oil recovery. [499] investigates the influence of organic agriculture development processes on Ukraine's economic security components. [500] assesses the bioenergetic efficiency of growing miscanthus with sewage sediment. [501] discusses the prerequisites for improving crop irrigation regimes based on resource optimization.

4.8. Business, economics, and sustainable development

Sustainable business practices and economic aspects of sustainable development are addressed in several papers. [502] proposes a mathematical model of the business process of higher education institutions based on ontological analysis. [503] explores creditworthiness management as a tool for ensuring sustainable, self-sufficient business development in Ukraine. [504] focuses on managing the economic security of food industry enterprises as a direction for ensuring sustainable development. [505] transforms the business ecosystem model into an energy enterprise's strategy. [506] analyzes the motivational profile of personnel directed at achieving sustainable enterprise development. [507] investigates sustainable consumption in times of war, focusing on needs, values, and possibilities. [508] proposes complex socio-economic solutions for the sustainable ecological development of Ukrainian regions. [509] discusses Ukrainian social sector development in contemporary conditions, highlighting problems and areas for their solution. [510] provides a comprehensive review of green accounting practices in India and global perspectives for advancing sustainable development. [511] identifies key competencies for post-war recovery and sustainable development of Ukraine's economy. [512] explores the interconnected roles of human capital, employment, and sustainable development in EU countries. [513] analyzes the income, consumer spending, and well-being of Ukrainian households. [514] explores project sustainability and sustainable project management in times of crisis, focusing on the context of the Russian-Ukrainian war. [515] models the energy security of the country in the context of sustainable development, using Ukraine as a case study.

4.9. Technology, materials, and modelling for sustainability

Various technological and material aspects of sustainability are addressed in the papers. [516] develops a dephosphorization technology for iron ores with high phosphorus content. [517] investigates melamine-doped TiO_2 as a perspective photocatalyst for hydrogen evolution. [518] studies the effect of sodium metasilicate on the early-age hydration and setting behaviour of alkali-activated common cement-containing slag. [519] explores the electrospark method of obtaining metal nanoparticles for creating antifungal drugs (fungicides). [520] designs rapid-hardening cementitious repair mixtures for increasing the sustainability of concrete structures. [521] investigates thermo-responsive hydrogels based on gelatin-alginate composition with humic acids intended for controlled drug delivery. [522] focuses on sustainable web API evolution and forecasting software development efforts. [523] conducts a comparative analysis and models safe variability areas of power for VVER-1000 and AP-1000 power units. [524] calculates electricity losses using neural networks for retrospective data with the presence of anomalous values. [525] forecasts air pollution by leveraging traffic modelling techniques. [526] applies chatbots to support indoor temperature control. [527] investigates the raw material base of crushed stone and rubble stone in the Khmelnytskyi region. [528] studies the influence of deformation degree on the efficiency of thin sheet cold rolling. [529] models cone crusher steady-state operation modes. [530] proposes modelling the process of ensuring the environmental sustainability of the airport as a functional component of socio-technical systems. [531] conducts experimental tests of the over-columned plates of the precast building frame. [532] investigates the effect of electrochemical impact on copper-molybdenum flotation separation. [533] conducts an experimental study of the effect of hydraulic gradient on soil hydraulic conductivity. [534] explores vegetation zone segmentation in multispectral imagery. [535] improves the evaluation of gamma radiation from cylindrical bodies with spatially inhomogeneous source activity distribution. [536] calculates round foundation slabs subjected to non-uniform base deformation under complex loads. [537] researches the effectiveness of using steel reinforcement for strengthening products made of natural stone. [538] investigates reducing the risk of power equipment failure when using information from the information measurement system of vibration diagnosis rotating units of auxiliary engines of power plants. [539] reviews the collapse behaviour of double-layer pipes. [540] proposes a technology for casting restoration by casting alloyed thermite melt onto the surface. [541] investigates changes in the intensity of polished surface glow of natural stone depending on the intensity of its heating. [542] presents a comprehensive approach to calculating operational parameters in hydraulic fracturing. [543] develops the modelling system core for severe plastic deformation processes. [544] explores harmful emissions of welding aerosol during pulse-arc welding of structural aluminium alloy D16. [545] investigates the propagation of elastic waves in cross-sectionally heterogeneous rods. [546] compares the seismic loading of points on the surface of the Earth during a massive explosion in a mine.

4.10. Hydrology, water management, and sustainable tourism

Hydrology and water management are the focus of several papers. [547] assesses the aesthetic and ecological functions of the urbanized part of small watercourses using the indicator of the visual quality of the environment. [548] investigates the issues of technological modelling of physicochemical iron removal from deep groundwater at the rapid filter. [549] explores the influence of war on the content of some components in the rivers of Ukraine. [550] analyzes trends in the variability of particulate organic carbon distribution in the north-western part of the Black Sea. [551] presents geoinformation modelling of the geoecological state of the floodplain-channel complex of rivers in the Turka city community of the Lviv region. [552] assesses the distribution and population characteristics of *Musculium lacustre* in anthropogenically altered aquatic landscapes of the northern right bank of the Dnipro River in Ukraine. [553] investigates the groundwater level dynamics in rice systems under different irrigation and drainage network parameters. [554] focuses on improving the efficiency of saline soil flushing under conditions of water resource scarcity. [555] analyzes the impact of water use and consumption for a nuclear power plant on alterations in the hydrological and temperature regimes of a river through a case study. [556] explores the regulation of water flow on the foothills of Ukrainian Carpathian rivers using flooded groynes. [557] applies numerical modelling for the interpretation of piezometric data on earth dams, considering uncertainties specific to dam operation. [558] analyzes current trends in water runoff of the Sluch River in terms of extraterritorial impacts of hydrotechnical construction. Sustainable tourism is represented by [559], which explores concession as a tool for improving budget and tax incentives for the investment attractiveness of the tourist complex in Ukraine. [560] proposes a new vision for ecological tourism in the industrial environment. [561] investigates sustainable development strategies in the field of tourism and recreation under war conditions in Ukraine. [562] identifies approaches to developing a response plan for potential emergencies caused by external water contamination. [563] investigates the influence of the accident at the Chornobyl nuclear power plant on the condition of pine plantations in Ukrainian forests. [564] designs a variable-structure controller for electric drives with ventilator torque.

4.11. Geology, mineralogy, and petrology

Geological aspects of sustainability are addressed in several papers. [565] proposes a concept for synthesizing the digital twin of a rock massif based on the stability criterion. [566] studies and analyzes amber deposits using ArcGIS techniques. [567] explores the features of mineral composition of garnet-bearing shales of the Kryvyi Rih basin and provides recommendations for further processing. [568] investigates the paleogeomorphological amber traps of the Prypiat amber-bearing basin in Ukraine, focusing on the theory and methodology of searches. [569] applies the geophysical method of NPEMFE for the preliminary geological outline of deposits of technological iron-containing raw materials. [570] studies the impact of low-molecular carboxylic acids on carbon dioxide corrosion of steel in underground gas production equipment in the Dnipro-Donetsk basin fields. [571] assesses the risks of soil foundation stability losses at the Kyiv-Pechersk Lavra Dormition Cathedral due to urban activities.

4.12. Sustainable energy solutions and waste management

Sustainable energy solutions are the focus of several papers. [572] explores the prospects for autonomous low-power renewable energy communities. [573] models and forecasts the production potential of renewable energy sources in the context of sustainable development. [574] proposes an electric drive of coordinated rotation for mechanisms of flow-transport systems. [575] determines the operating parameters of accumulative electric heating systems. [576] studies double short circuits on earth in 10 kV power grids with isolated neutral and high-level penetration of renewable energy sources. [577] discusses the postwar perspective of ammonia production in Ukraine. [578] analyzes the current state and prospects of renewable energy in heating and cooling systems in Ukraine. Waste management is addressed by [579], which focuses on the utilization of vegetative waste from the green infrastructure of cities "in-situ". [580] explores the prospects of recycling metallurgical waste. [581] investigates the natural phytomelioration of coal mine waste heaps in the context of increased radiation background, focusing on the case of the Nadiya mine in the Lviv-Volyn coal basin, Ukraine. [582] proposes increasing the level of an ecologically oriented logistics system in waste management for territorial communities. [583] explores gypsum recycling using an inclined chamber vibrating jaw crusher. [584] explores radioecological monitoring as a critical factor in food quality management. [585] discusses the methodology for improving the concept of maximum security of a nuclear facility at minimum costs. [586] investigates the features of designing systems for the formation of an internal microclimate of a high class of cleanliness in operating rooms of medical institutions. [587] explores climate factors and their role in the development of wind energy in the Lviv region. [588] analyzes the current state and development prospects of the graphite industry in Ukraine. [589] revisits the mathematical model of the process of self-destruction of outburst-prone coals under hydrodynamic effect.

5. Conclusion

The vision driving ICSF 2024 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.

A special acknowledgement goes to the session chairs, whose steadfast commitment to shaping the conference and its program has been exceptional. Their role has contributed significantly to the cohesive and productive flow of the conference sessions.

Furthermore, we express our gratitude to IOP Publishing for their generosity in waiving the APC payments for corresponding authors based in Ukraine. This initiative enables authors to publish open access without charge in the prestigious *IOP Conference Series: Earth and Environmental Science* journal (`https://iopscience.iop.org/journal/1755-1315`). Additionally, the submission extensions offered by IOP Publishing are a testament to their understanding of researchers' challenges and constraints, underscoring their dedication to fostering a supportive academic environment.

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 2025. The next instalment in the series, the 6th International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters, is set to take place in May 2025 in Kryvyi Rih, Ukraine (`https://icsf.easyscience.education/2025/`).

Thank you all for being an integral part of ICSF 2024, and here is to a brighter, more sustainable future that we collectively strive to build.

Acknowledgments
We want to acknowledge the contributions of our late colleague, Serhii Mykhailovych Chukharev, a distinguished scholar and dedicated educator who passed away before this work was published.

Figure 2. Prof. Serhii Mykhailovych Chukharev (04/17/1958 – 08/30/2024).

Born on April 17, 1958, in Kropyvnytskyi (formerly Kirovohrad), Serhiy Mykhailovych was a beacon of knowledge and inspiration in the field of mining engineering.

Serhii Mykhailovych graduated from Kryvyi Rih Mining Institute in 1981, earning his degree as a mining engineer-builder. His academic journey continued with the defence of his PhD thesis in 1989, marking the beginning of a prolific career in academia and research. In 1996, he furthered his education by obtaining a second degree in finance and credit, showcasing his versatile intellect and commitment to lifelong learning.

Throughout his career, Serhii Mykhailovych held esteemed positions, including Associate Professor at the Department of Underground Mining of Mineral Deposits at Kryvyi Rih National University and later at the National University of Water and Environmental Engineering. His contributions to the field are immortalized in over 100 scientific and methodological works, including five patents.

Serhii Mykhailovych's research focused on developing innovative technologies and methodologies for the sustainable and efficient extraction of mineral resources. His early works explored the application of vibration mechanisms for forming asymmetric draw figures and the feasibility of this process. He also contributed to the development of a method for mining mineral deposits.

In the 1990s, Serhii Mykhailovych's research expanded to include the development of self-propelled equipment in the mining industry, the technology of extracting under-quarry ore reserves and improving the technology for extracting ore from the underground tier. He also investigated the patterns of formation of the drawing figure for ores with different physical and mechanical properties and the possibility of increasing the stability of the receiving horizon.

In the 2000s, Serhii Mykhailovych's research focused on using communication technologies to improve the efficiency of working with corporate bank clients and applying marketing to the creation and implementation of scientific and technical products.

In recent years, Serhii Mykhailovych's research has centered on the development of resource-saving mining technologies, the enhancement of the stability of mine workings during their excavation and operation in complex mining and geological conditions, and the selective mining of complex-structured ore deposits of the Kryvyi Rih basin.

Serhii Mykhailovych was not only a respected academic but also a mentor and guide to many students and colleagues. His dedication to advancing mining technology and resource-saving methods has left an indelible mark on the industry.

He is survived by his family, friends, and countless students who will remember him for his wisdom, kindness, and unwavering dedication to education and research.

May his soul rest in peace, and may his legacy continue to inspire future generations.

Serhii Mykhailovych was a valuable member of our research team and significantly contributed to this project. We miss him dearly.

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Methane degassing within Ukraine according to satellite data

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Abstract. The article substantiates the concept of degassing the Earth using the example of methane, a gas component of the fluid regime of the lithosphere. According to the analysis of observations from the Sentinel-5P satellite over the territory of Ukraine for the period 2019-2022, data on the distribution of methane (CH_4) in the atmosphere were obtained using the Google Earth Engine (GEE) platform, and a corresponding map was compiled. The distribution of methane content within the main tectonic structures of Ukraine is very complex and is probably not related to the specifics of their development. It has been established that methane is present everywhere in the atmosphere of Ukraine but in different amounts. The relationship between the content of methane in the atmosphere and the content of hydrocarbons within 12 known oil and gas-bearing areas of the Dnieper-Donets Depression (DDD) was established. Two aggregates are distinguished: areas with the largest reserves of hydrocarbons and oil and gas-bearing areas with low reserves of hydrocarbons, which are characterized by a significant range of changes in the content of methane in the atmosphere. This indicates the connection of methane content in the atmosphere with hydrocarbon reserves in oil and gas-bearing areas. That is, the process of degassing is taking place and it can be studied according to the remote sensing (RS) data.

1. Introduction

Global and regional (Ukraine) climate warming, especially in recent years, causes concern in the world community, as the consequences of these changes threaten serious natural disasters (intensification of natural phenomena: increase in droughts, floods, fires, etc.). Therefore, recently, the problem of creating an indication base of global and regional changes in the Earth's climate for their forecast and adaptation to the development of these events in the future is becoming more and more urgent. As many researchers have shown, such a geophysical factor as a change in the gas composition of the atmosphere has a significant impact on the Earth's climate change. The process of degassing the Earth has a decisive influence on the change in the gaseous composition of the atmosphere. Deep degassing of the Earth is a leading planetary process that has occurred throughout the entire history of the planet's development. In this study, we will consider the geophysical factor associated with the processes of degassing from the Earth's interior. In recent decades, more and more attention has been paid by scientists of all countries to the study of the processes of degassing of the Earth, which influenced the geological development of the Earth, as well as its weather and climate conditions [1–10].

Degassing processes play an important role in the formation of deposits of various minerals, not only oil and gas deposits but also ore – endogenous, partly exogenous, and mineral water deposits. In addition, degassing processes, primarily hydrogen degassing, play an important structure-forming role in geodynamic processes. Mechanisms of structure formation in the crystalline basement and sedimentary-volcanogenic shell are associated with dilation processes, which are quite diverse [11].

The composition of the gases released in the degassing process is very diverse, including methane and other hydrocarbon gases, carbon dioxide, sulfur gases, hydrogen, radon, helium, argon, oxygen, mercury vapor, etc. In recent years, researchers have paid considerable attention to the study of hydrogen, which has a significant impact on both climatic and geological processes. In the process of degassing the Earth, there is a simultaneous emission of gases of different compositions. The combination of gases of different compositions within one emission is not accidental, it is probably related to their genetic unity. The impact of degassing on the weather and climate conditions of the planet is evidenced by the fact that the centers of the strongest anomalies in the ozone content of the planet are located above the zones and centers of hydrogen and methane degassing. These are rift and fault zones or nodes of their intersection, as well as centers of modern tholeiitic and alkaline volcanism or ancient ultramafic (kimberlite) volcanism [12].

As a result of the natural degassing of the Earth, the content of hydrogen and methane outside the accumulation of hydrocarbons turns out to be quite strongly interconnected. This allows us to talk about the single depths of their generation [13].

As a result of diffusion and filtration processes, gas aureoles are also formed around not only hydrocarbon deposits but also solid minerals deposits. The size of these aureoles significantly exceeds the size of other geochemical aureoles. During the movement of gases through rocks characterized by different porosity, gas separation occurs. This is best seen from the example of hydrocarbon gases. Lighter and less sorbed components move faster through rocks, overtaking heavy and better-sorbed ones. As the results of the conducted experiments showed, during the movement of hydrocarbon gases, their division into methane, ethane, propane, and butane occurs [11].

The process of degassing the Earth is divided into hot and cold degassing, which differ not so much in temperature as in oxidation-reduction parameters. Cold degassing is characterized by geochemical processes involving reduced (hydrogen-hydrocarbon-based) fluids, while the main factor in hot degassing is hydrogen oxidation under conditions of high temperature gradients. Cold degassing determines the paragenetic associations of hydrocarbons, helium, and hydrogen [11, 14, 15].

It is assumed that the main factor in the processes of degassing are endogenous energy flows of various nature, coming from the depths of the Earth to its surface, which create conditions for the movement of fluids [16]. The most important feature of this process is its unevenness both in time and space. Based on modern observations, the power of gas emissions can spontaneously increase millions of times, and the area of such a gas-dynamic disturbance can reach hundreds of thousands of square kilometers. In addition, a pattern common to the entire planet has been established – increased hydrogen release at the end of the year, when the Earth is at perihelion in its orbit around the sun, while at aphelion the maximum frequency of volcanic eruptions [12].

The volumes of gases released in the process of global degassing of the Earth undoubtedly influenced the component composition of the atmospheric air, especially in the surface layer. Currently, the most significant influence on the composition of the atmosphere is provided by the influx of hydrogen, methane, and carbon dioxide. The introduction of hydrogen into the atmosphere leads to changes in the ozone layer of the atmosphere, which contributes to the emergence of tropical cyclones and climate warming [17].

The indicator in this study will be the gas component of the fluid regime of the lithosphere –

methane. Research of CH_4 emissions began to be conducted already in the early 1930s, when V. O. Sokolov proposed the theoretical and applied principles of gas surveying to find hydrocarbon deposits. In the subsequent study of methane content, along with the solution of search problems, they were also used to study the laws of the Earth's development and to solve environmental problems.

Already the first works on the study of the content of methane in the atmosphere established that many different factors have a significant impact on its content, which are not always possible to take into account. Research was conducted exclusively based on ground observations, which were carried out on relatively small areas, for a relatively small amount of time and only during a certain period of the year. To calculate the effect of various factors, and their quantitative estimates, which affect the methane content, as is known, it is necessary to conduct research for a long time in the monitoring mode. Such an opportunity to quickly and economically conduct such research is provided by the use of only data from space surveys.

Taking into account the significant variability of the Earth's degassing processes, both in time and in space, a long-term series of observations are needed to study this process and assess its impact on climate processes, i.e., work in the monitoring mode. Such an opportunity is provided only by the use of space survey materials. However, as is known, the use of materials from space photography appeared relatively recently, and before that, the only source of studying the gaseous respiration of the Earth was the results of ground measurements of gases. Although such methods provide fairly accurate determinations of the content of various gases, they are very time-consuming and were carried out selectively in small areas. These are primarily the materials of the gas survey, which was carried out only in areas where mineral deposits are located, before all oil and gas deposits. In addition, the materials of the emanation survey, which was carried out during the search for ores of radioactive metals. Therefore, this study, is planned to jointly use these two sources of information about the gaseous respiration of the Earth with a wider use of materials from space image.

2. Materials and methods

Data on the concentration of methane CH_4 in the atmosphere over the territory of Ukraine for the period 2019–2022 were used, which were obtained from the Sentinel-5P satellite, using the Google Earth Engine (GEE) platform.

To interpret the results of remote research data, the results of ground research were used: scheme of the oil and gas geological zoning of the Dnieper–Donetsk oil and gas-bearing region [18] and map of the tectonic zoning [19].

With the use of geoinformation software, the following was done: 1) all geological data are presented in the UTM / WGS 84 zone 36 coordinate system; 2) nine main tectonic structures of Ukraine were vectorized based on the tectonic zoning map (figure 1); 3) according to the oil and gas geological zoning scheme of the Dnipro–Donetsk oil and gas-bearing region, vectorization of twelve oil and gas regions was carried out. This is the most reliable material on the content of hydrocarbons on the territory of Ukraine. The sizes of the districts allow to receive reliable data from the satellite. Each of the districts is marked with a Latin letter from A to O. Methodical approaches were previously tested in the work [20].

3. Results

The relationship between the content of methane in the atmosphere and the content of hydrocarbons within the oil and gas-bearing areas of the DDD, established by drilling data, was analyzed [18]. Distributions of methane content in the atmosphere were compiled for each of the districts and the average value was calculated. Graphs were drawn (figure 2 and figure 3) to establish the relationship between the content of methane in the atmosphere and the content of hydrocarbons within the territory of oil and gas-bearing regions.

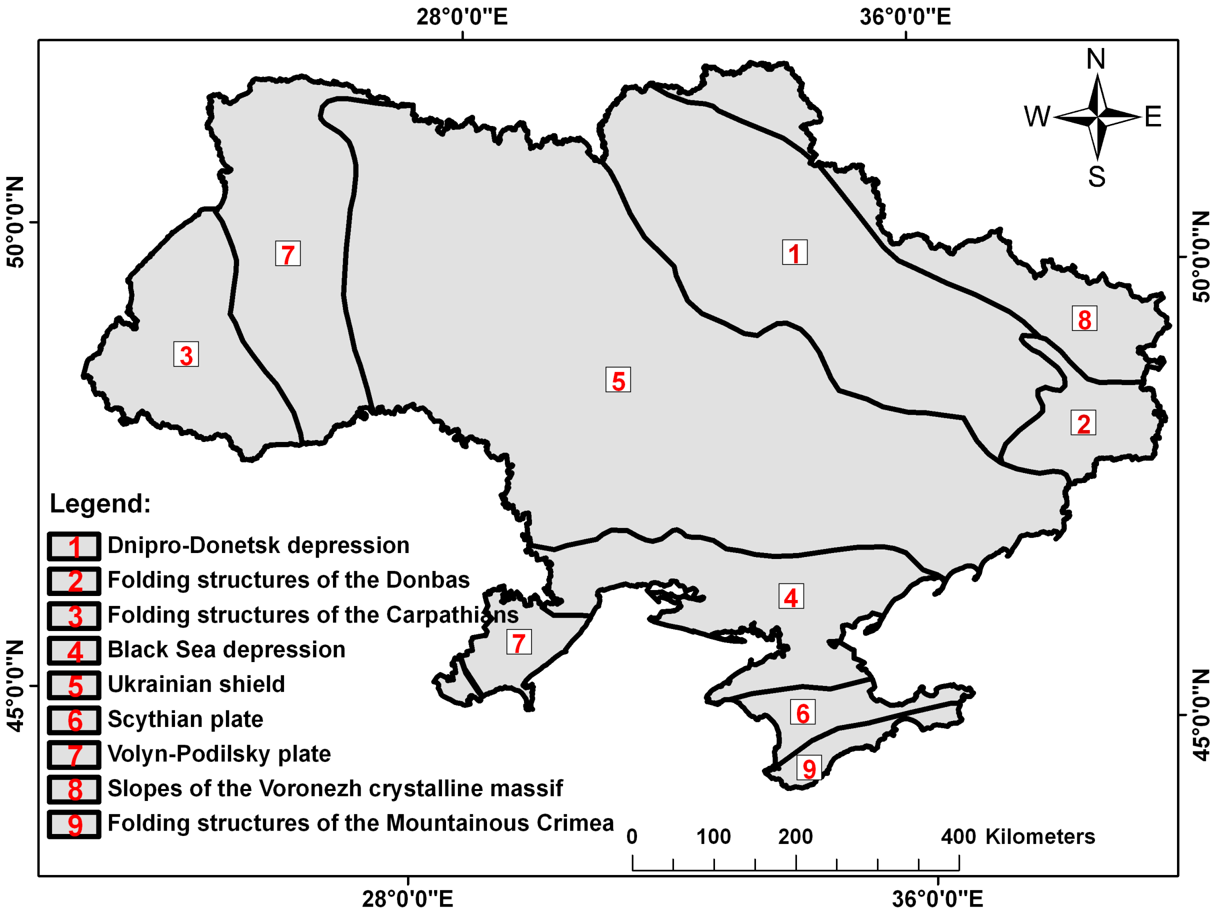

Figure 1. Vectorized contours of nine main tectonic structures of Ukraine according to [19].

The first graph (figure 2) analyzes the dependence of methane content on the size of oil and gas-bearing areas.

The second graph (figure 3) shows the relationship between the specific reserves of hydrocarbons (million tons / km^2) within each oil and gas-bearing region of the DDD and the methane content in the atmosphere above these regions.

The general regularities of the distribution of methane on the territory of Ukraine were evaluated using the Google Earth Engine (GEE) platform based on calculations of the CH_4 methane concentration in the atmosphere for the period 2019-2022. The data were obtained from the Sentinel-5P satellite and combined with the contours of the main tectonic structures of Ukraine (figure 4).

4. Discussion

Analysis of the data received from the Sentinel-5P satellite shows that methane is found in the atmosphere of Ukraine over the entire territory, with the exception of the Carpathian Mountains and Crimea.

The compiled graph (figure 2) shows that the methane content in the atmosphere does not depend on the size of the areas of oil and gas-bearing regions DDD.

The analysis of the compiled graph (figure 3) proved that all Oil and gas-bearing regions DDD are reliably divided into two groups. The first group included 7 districts (I, L, E, K, O1, B, A), and the second group included 5 districts (G, H, F, D, C).

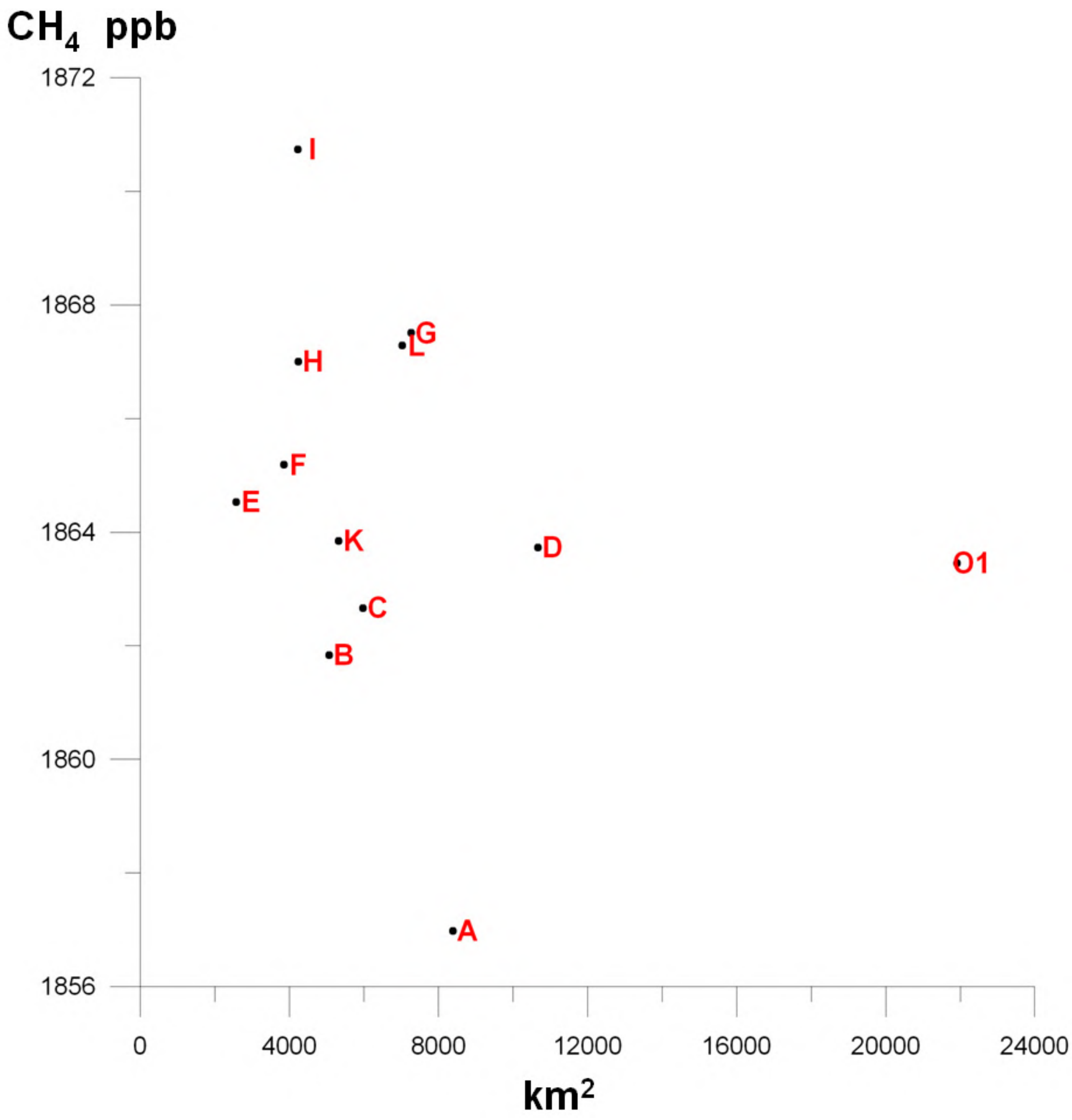

Figure 2. Dependence between the size of the oil and gas-bearing regions of the DDD and the content of methane in the atmosphere. Legend: oil and gas-bearing areas: A – Chernihiv-Braginsky prospective, B – Monastyryshche-Sofiivka oil-bearing, C – Talalaivka-Rybalske oil-and-gas bearing, D – Glynsk-Solokha gas-bearing, E – Antonivka-Bila Tserkva oil-and-gas bearing, F – Ryabukhyne-Northern-Golubivka gas-bearing, G – Mashivka-Shebelynka gas-bearing, H – Rudenky-Proletarske oil-and-gas-bearing, I – Zhovtneve-Lozivka prospective, K – Spivakivka gas-bearing, L – Kalmius-Bakhmut gas-bearing, O – oil and gas-bearing of the northern edge.

Oil and gas-bearing regions of the first group (I) are characterized by minimal hydrocarbon reserves and the maximum difference in methane content. Thus, extreme (maximum and minimum) values of methane content are marked by two regions (A, I) within which no

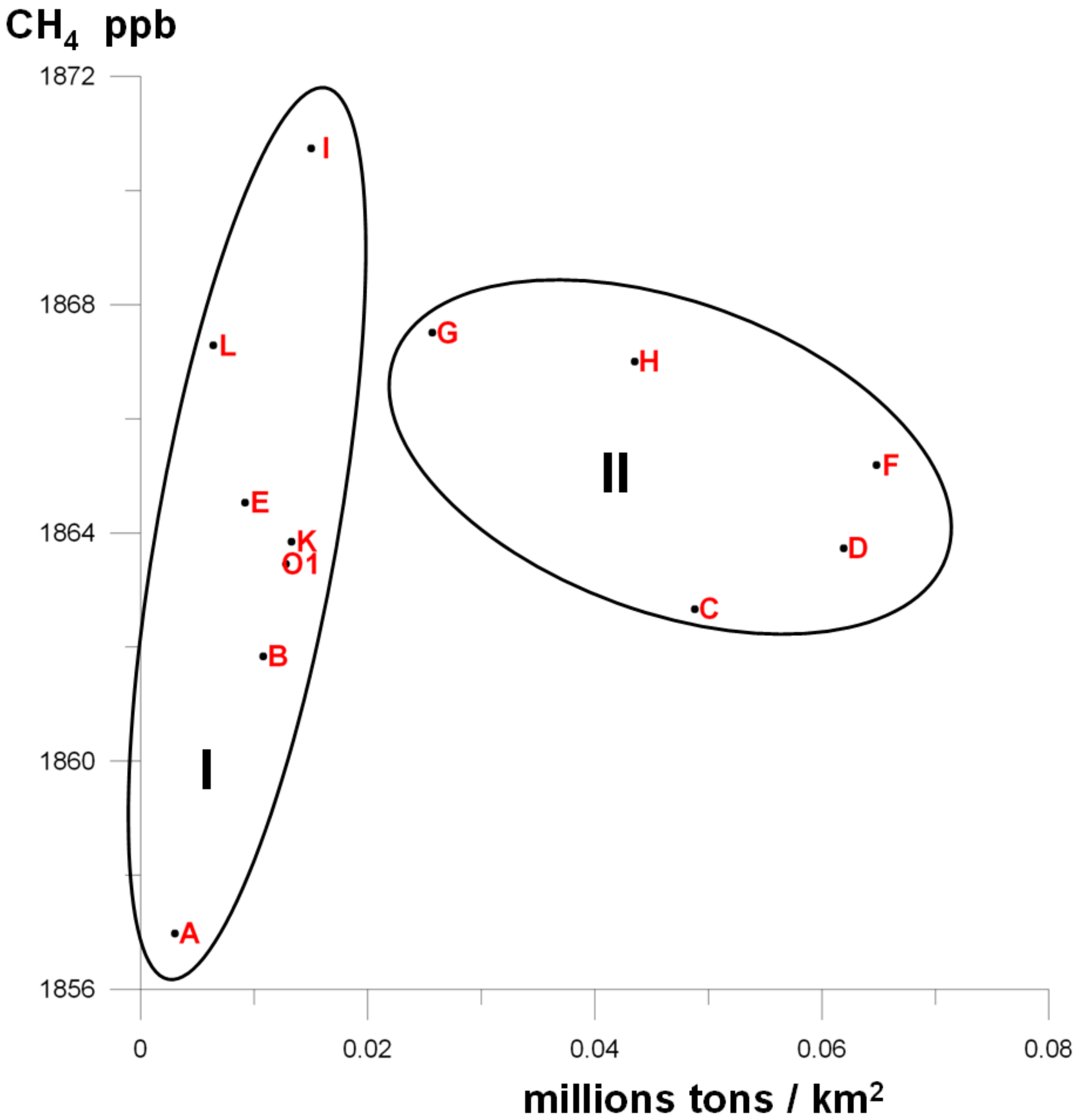

Figure 3. Dependence between the specific reserves of hydrocarbons in the oil and gas-bearing regions of the DDD and the content of methane in the atmosphere.

hydrocarbon deposits have been established. Significant differences in methane content within the regions of the first group are probably caused by corresponding differences in the permeability of the rocks that make up these regions. Thus, in the districts of the first group, there is no dependence between the size of methane reserves within their boundaries and the values of methane content.

Oil and gas-bearing areas of the second group (II) are characterized by the highest values of hydrocarbon reserves within the boundaries. Within their boundaries are also the largest DDD deposits in terms of reserves. At the same time, with an increase in the values of specific reserves of hydrocarbons within the oil and gas-bearing regions, there is a decrease in the content

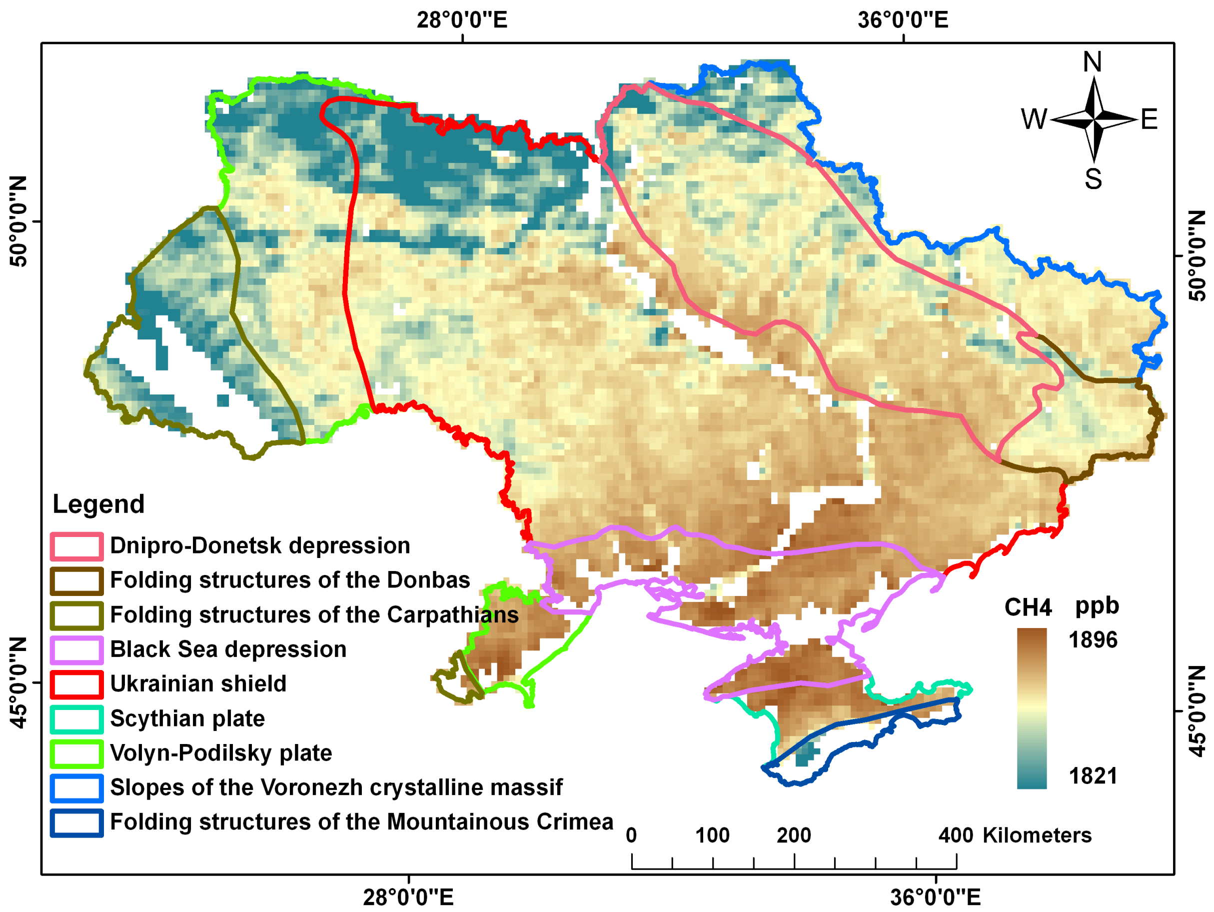

Figure 4. Spatial distribution of methane concentration over the territory of Ukraine according to data from the Sentinel-5P satellite for 2019-2022.

of methane in the atmosphere. Such a dependence is possibly related to the lower permeability of the rocks of the regions and the presence within these oil and gas-bearing regions of the best local structures within which the maximum localization of hydrocarbons migrating in the earth's crust occurs.

Thus, the conducted studies clearly indicate the connection of methane content in the atmosphere with the content of hydrocarbon reserves within oil and gas-bearing regions. This relationship is quite complex. In the future, we consider it expedient, in addition to methane, to investigate the content of other gases associated with hydrocarbon deposits.

A visual analysis of the compiled map (figure 4) proved that methane is found in the atmosphere throughout the territory of Ukraine, there are no areas where methane is absent. The content of methane naturally increases from the north-northwest to the south and southwest. This excludes the influence of vegetation, swamps, and other anthropogenic factors on the recorded content of methane in the atmosphere. Based on the connection established by our predecessors between the presence of methane and the processes taking place in the bowels of the Earth, the influence of the history of the development of individual regions on the content of methane in the atmosphere was analyzed. As a tectonic scheme, the scheme given in [19] was used. The diagram highlights 9 main tectonic structures.

According to the average content of methane and the nature of its distribution, the selected tectonic structures were divided into 3 groups. The first group, with maximum methane values, includes the Black Sea Basin of the Cretaceous-Paleogene age and the Scythian plate of the Epipaleozoic age. The second group with intermediate values of methane content includes the Variscids of the Donbas, the Precambrian Ukrainian Shield, and the Mesozoic Basin DDD. The slopes of the Voronezh crystalline massif of the Precambrian age, the Riphean Volyn-Podilsky plate, the Alpine folded structures of the Carpathians and the Mountain Crimea of the Kimmerian-Alpine age are characterized by the lowest values of methane content. The given data indicate that there is no connection between methane content and the nature of the development of tectonic structures, because one group includes tectonic structures with a completely different history of development. The distribution of methane is probably influenced by other geological factors and, above all, by faults.

A comparative analysis of methane distribution within known oil and gas-bearing areas – western (Carpathian), southern (Scythian Plate), and eastern (DDD) showed significant differences between them. The western area is characterized by the lowest average values of methane content. The southern area is characterized by the highest values of methane content, and the eastern area is characterized by intermediate values of methane content. The established discrepancies are probably related to known peculiarities in the localization of hydrocarbon deposits within these three areas, but this needs to be further analyzed [18].

5. Conclusions

According to the data of measurements of methane content in the atmosphere of Ukraine from the Sentinel-5P satellite, a map of the distribution of methane within the country was compiled.

The existence of a dependence between the content of methane in the atmosphere and the content of hydrocarbons within the oil and gas-bearing regions of DDD has been established. The most productive oil and gas-bearing regions of DDD are characterized by a relatively narrow interval of changes in the methane content in the atmosphere.

The distribution of methane content within the main tectonic structures of Ukraine is very complex and is probably not related to the specifics of their development. This problem needs further research.

Based on the conducted research, it can be confidently stated that there is a rather complex relationship between the reserves of hydrocarbons in the lithosphere and the content of methane in the atmosphere.

In further studies of the processes of degassing of the Earth, it is expedient to study, in addition to methane, other gases that are part of the gases released by the Earth's surface and which are genetically related to each other, as well as the thermal field and other physical fields.

The research of Earth degassing processes provides additional data for understanding problems related to climate change, namely the composition of the atmosphere, as well as established dependencies that can be used as additional information when searching for hydrocarbon deposits.

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Patterns of PM10 particles change in the atmospheric air of Ivano-Frankivsk city

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Abstract. PM is one of the main atmospheric air pollutants causing serious concern for public health. New evidence on health effects of PM has led to the publication of new WHO air quality guidelines. Spatio-temporal patterns of PM10 change are a current topic in atmospheric and environmental sciences. An equally important aspect is the study of the relationship between PM10 concentration and meteorological characteristics. Temperature, humidity, wind and atmospheric pressure can affect the concentration, distribution and transport of PM10. The database for the study included measurements of PM10 concentration, air temperature, atmospheric pressure, and relative humidity for 306 days in 2019 (from March 1 to December 31) every hour, a total of 7,344 for each parameter from the Ecocity public monitoring station in the central part of Ivano-Frankivsk city. There are no significant stationary pollution sources and highways near the observation site. Certain regularities were found in the daily variation of PM10 concentration: sharp increase in concentrations at night with a peak around midnight, decrease during the day (minimum around 16:00). The proposed sinusoidal model fairly well reflects the distribution of data in the morning hours, from 5 to 11 am. Significant fluctuations in daily concentrations (from 0 to 100 μg/m^3) were observed, especially in the cold period of the year. The highest average monthly values of PM10 are in March, the lowest are in July. The current average daily limit value in Ukraine and the EU is 50 μg/m^3 (no more than 35 exceedances per year), 442 instantaneous indicators above the norm. When analyzing the relationship between PM10 concentrations and air temperature, the regularity is observed both during the day and throughout the year (in cold periods, the concentration of particles is higher, which can be explained by lower air temperatures). The patterns identified are related to a number of factors, such as meteorological conditions, pollution sources, and atmospheric chemistry. Multivariate linear regression was used to find the mathematical relationship between the average monthly values of PM10 concentration, humidity and air temperature. The coefficient of determination $R^2 = 0.67$, Fisher's test F = 70.95 and the mean square error MSE = 23.12. On the basis of this, it can be stated that the model is acceptable for estimating and forecasting temporal patterns of the concentration of PM10 particles in the atmospheric air of Ivano-Frankivsk, depending on the average monthly indicators of humidity and atmospheric air temperature.

1. Introduction

Solid particles PM (eng. Particulate matter) belong to the main pollutants of atmospheric air, which cause serious concern for health [1]. These are respirable particles that consist of sulfate, nitrate, ammonia, sodium chloride, carbon black, mineral dust, or water. According to their classification by aerodynamic diameter, PM10 are particles whose diameter does not exceed 10 micrometers. Due to their small size, they are able to penetrate deep into the lungs and enter the blood, causing cardiovascular, cerebrovascular, respiratory and other diseases [2–4].

The sources of PM10 in the atmospheric air can be natural processes, but mainly they are the anthropogenic factors. Despite the EU's 2021 emission reductions, the majority of the urban population was still exposed to key health-damaging air pollutants. Concentrations exceeding the EU daily limit value for PM10 are observed mainly in Italy and some Eastern European countries, in particular due to specific meteorological and geographical conditions that contribute to the accumulation of air pollutants in the atmosphere of densely populated and industrialized areas, the extensive use of solid fuel for heating households, at industrial enterprises and thermal power plants [5].

Many states have their own national or supranational agencies that develop programs, policies, and regulations for air pollution control [6–8]. Given the impact on health, the openness and availability of official data on atmospheric air pollution is a prerequisite. Geoinformation applications such as the European Air Quality Index [9] or the Ambient Air Quality Database Application [2] allow interested parties to get an idea of air quality in individual countries, regions and cities.

The study of spatio-temporal patterns of PM distribution in the atmosphere is an important field of natural sciences. Such research is conducted by scientists, institutes and organizations around the world. NASA [10] and other space agencies, as well as private companies, use satellite data [11] to monitor and study particulate matter in the atmosphere at national and global levels. This includes the study of their sources, processes of transfer and transformation.

It is interesting from a scientific point of view to study the spatio-temporal patterns of PM10 distribution in the atmospheric air, taking into account the patterns of changes in the meteorological characteristics of the atmosphere [12]. Spatio-temporal patterns of particle distribution may differ depending on the region, climatic conditions, local sources of pollution, etc. [13]. Therefore, local research is also of a great importance [14]. This work is dedicated to the partial solution of these problems.

2. Literature review

Most of the scientific works deal with the study of the PM impact on human health. A systematic reviews collection of the latest scientific research concerning the air pollutants effects on health [15] formed the basis for the publication of new WHO air quality guidelines [4]. Regarding the new evidence of PM health effects, it is worth noting the work [16], which conducted a systematic review of 104 cohort studies on the evidence of the relationship between long-term exposure to PM2.5 and PM10 in relation to all-cause mortality and mortality from a specific cause. There was clear evidence that both PM 2.5 and PM 10 were associated with increased mortality from all causes, cardiovascular disease, respiratory disease and lung cancer, with associations at lower concentrations for the limit value of PM 2.5 of 10 $\mu g/m^3$ recommended by WHO until 2021. A study [17], in which a systematic review and meta-analysis of 196 scientific articles was conducted, found evidence of a positive association between short-term exposure to PM10, PM2.5, NO_2, and O_3 and all-cause mortality, as well as between PM10 and PM2.5 and mortality from cardiovascular, respiratory and cerebrovascular diseases.

Spatio-temporal patterns of PM10 change are a current topic in atmospheric and environmental sciences. An analysis of some works is presented below.

Fioravanti et al. [18] illustrates the main results of the process of spatial-temporal interpolation of PM10 concentration with a daily resolution using a set of 410 monitoring locations in Italy for 2015. The result of the model is a set of 365 daily PM10 maps of Italy with a grid (1 km×1 km).

Chu, Huang and Lin [19] investigated spatiotemporal patterns (PM) in Taiwan based on a number of methods (global ordinary least squares regression, geographically weighted regression, and geographically and temporally weighted regression). PM2.5 or PM10 have been found to vary over time and space, depending on weather conditions and the spatial distribution of land use and emission patterns in local areas.

Satellite-based measurements of aerosol optical depth offer the possibility of estimating impacts on populations in locations without monitoring stations, as assessed by Nordio et al. [20], in which scientists extend their previous research by including a model for missing aerosol optical depth data to combat non-randomness of missing data. The use of spatio-temporal hydrometeorological parameters modeling methods is presented in the article by Pernerovska and Arkhypova [14].

An analysis of spatial and temporal pollutants variations and their possible sources in urban areas of Istanbul [21] showed that PM10 concentrations demonstrate significant variations across the city, with current PM10 levels in several traffic hotspots and industrial areas exceeding EU air quality limit. The temporal distribution was characterized by high concentrations in winter and low in summer.

An equally important aspect is the study of the relationship between PM10 concentration and meteorological characteristics. Meteorological conditions such as temperature, humidity, wind and atmospheric pressure can affect the concentration, distribution and transport of PM10.

Huang et al. [22] studied seasonal changes and their impact on aerosol concentrations. The results revealed pronounced seasonal variability in fine particles (aerodynamic diameter less than 2.1 μm), with the highest concentration in summer and the lowest in spring.

Kayes et al. [23] studied the relationships between the average daily temperature, relative humidity, precipitation and concentrations of the main air pollutants in the city of Dhaka according to data from the period 2013-2017. The main results are a negative correlation of PM2.5 and PM10 concentrations with temperature and relative humidity; different effects of meteorological parameters' seasonal fluctuations on the air pollutants concentration; the adequacy of various models application for the solid particles modeling.

3. Materials and methods

Maximum permissible concentrations of PM10 in atmospheric air are established to protect human health and the environment. Air quality standards in the EU regarding PM are determined by Directive 2008/50/EC "On ambient air quality and cleaner air for Europe". In Europe the limit value of the daily PM10 concentration should be 50 $\mu g/m^3$ (no more than 35 excesses per year), and the average annual value should be 40 $\mu g/m^3$. In 2021, based on new evidence of low pollutants concentrations on the health effects, WHO issued new guidelines for air quality [4], with a daily average limit value for PM10 of 45 $\mu g/m^3$ and an annual average limit of 15 $\mu g/m^3$. According to them, the EU standards are currently being revised.

So far, in Ivano-Frankivsk city, which is a regional center with a population of about 250,000 people, there is no systematic state control of PM10 concentration. There is one stationary air quality monitoring post in Ivano-Frankivsk Regional Center for Hydrometeorology of the State Emergency Service of Ukraine. Here, pollutant concentrations are measured four times a day (at 01:00, 07:00, 13:00, 19:00), the content of general dust (undifferentiated by size), SO_2, NO_2, CO is assessed. Also, the state institution "Ivano-Frankivsk Regional Center for Disease Control and Prevention of the Ministry of Health of Ukraine" monitors the atmospheric air pollution condition at 20 route observation points on the border of enterprises sanitary protection zones, within residential buildings, in the influence of highways zone, etc. [24]

In recent years, Ukraine began to bring its legislation into line with European standards, therefore, in the new procedure for state monitoring in the field of atmospheric air protection [25], it implemented Directive 2008/50/EC. According to it, the system of state monitoring is gradually being modernized.

In 2023 Ivano-Frankivsk City Council approved the State Monitoring Program in the field of atmospheric air protection of the Ivano-Frankivsk agglomeration for 2023-2027 [26]. The program provides for the modernization of the atmospheric air quality monitoring system, but this requires significant capital investments, the purchase and installation of a complex of equipment at a stationary observation point for automatic operational fixed measurements.

The aim of our research was to establish spatio-temporal regularities in the distribution of solid particles (PM) and the meteorological parameters of atmospheric air.

Due to the lack of necessary data from official sources, data from public monitoring of atmospheric air quality became a substitute. For this, we used the database of the Ukrainian network of public air quality monitoring – Eco City [24]. Starting in 2019, about ten such online monitoring stations were installed within Ivano-Frankivsk city. Each monitoring station in real time analyzes the content of such pollutants as PM10, PM2.5, CO, SO_2, NO_2, etc., as well as meteorological parameters of atmospheric air.

To achieve the goal of our research, we developed a database for one Eco City public monitoring station for 2019. The station is located in the central part of Ivano-Frankivsk within the historical and architectural protected territory of local importance. There are no significant stationary pollution sources and highways near the observation site (figure 1). The database included hourly measurements of PM10 concentration, air temperature, atmospheric pressure, and relative humidity for 306 days in 2019 (from March 1 to December 31) every hour, with a total of 7,344 measurements for each parameter.

Figure 1. Location of public air quality monitoring station.

4. Results and discussion

Based on the average hourly PM10 concentrations determination for the studied period (306 days), certain regularities in the daily concentration change were established (figure 2). At night (from 00:00 to 05:00) there is a sharp decrease in concentrations, in the morning (from 06:00 to 09:00) concentrations begin to increase and stabilize (from 10:00 to 11:00). During the day (11:00 a.m. to 5:00 p.m.) concentrations continue to decrease, reaching a minimum around 4:00 p.m. In the evening (after 18:00) concentrations increase again, reaching a peak at midnight.

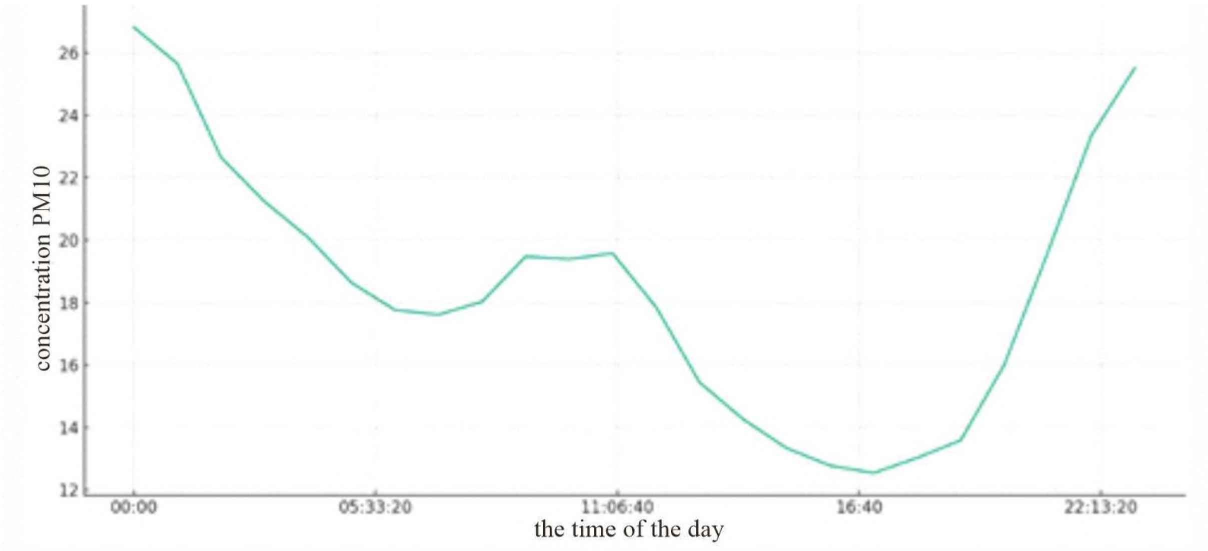

Figure 2. Daily change of PM10 concentration.

These data may indicate certain daily patterns in PM10 distribution, in particular, related to human activity and meteorological conditions. Different approaches can be used to find the mathematical regularity of the PM10 daily distribution, one of the approaches is data modeling functions use. Since the daily distribution is cyclical in nature, the sinusoidal function can serve as one of PM10 daily distribution expressions. Using a sinusoidal function of the form:

$$y(t) = A\sin(B(t + C)) + D \tag{1}$$

where A is amplitude, B is frequency, C is phase shift, D is vertical shift, t is time (h).

The equation that describes the sinusoidal model for the daily distribution of PM-10 dust particles:

$$y(t) = -1.256\sin(1.435(t - 1.610)) + 18.433 \tag{2}$$

where $y(t)$ – concentration of PM10 (μg/m^3), t is time (h).

Figure 3 is a visualization of both actual and predicted PM10 values to see how well our model represents the diurnal distribution. As you can see, the sinusoidal model fairly well reflects the distribution of data in the morning hours, from 5 to 11.

To find the relationship between PM10 concentration values and air humidity, we will try to use linear regression. This will allow us to understand whether there is a direct or inverse relationship between these two quantities. To get an idea of their dependence, we visualize these two values on a scatter plot (figure 4).

The distribution shows that the relationship does not appear to be linear, but there is probably some correlation between these two quantities. The following linear regression model

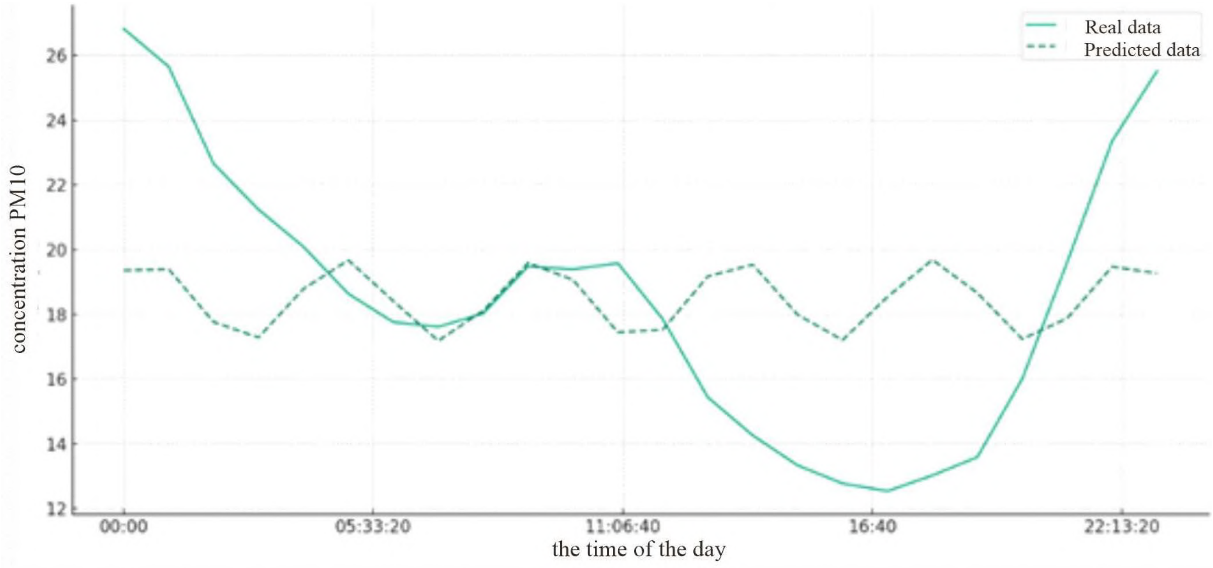

Figure 3. Real and predicted PM10 daily distribution.

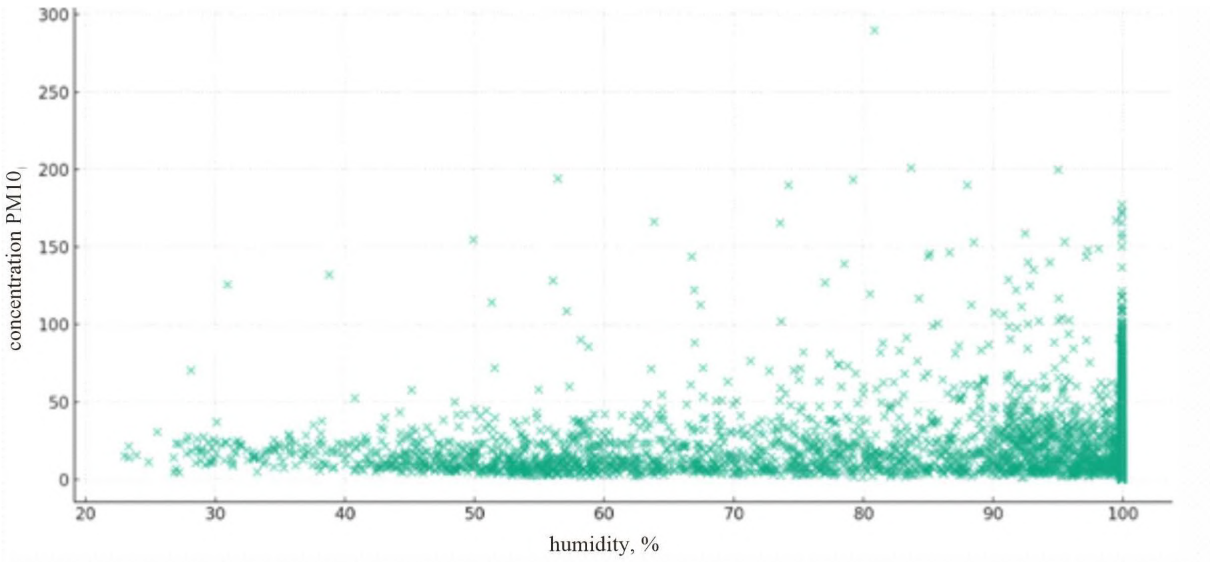

Figure 4. Dependence of PM10 concentration on air humidity.

was obtained:

$$y = -0.0117 \cdot h + 20.32y = -0.0117 \cdot h + 20.32 \tag{3}$$

where y is the PM10 concentration (μg/m^3), h is the relative air humidity (%).

The coefficient of determination R^2 for this model is very small (about $9.23 \cdot 10^{-5}$), which indicates that there is no linear direct or inverse relationship between PM-10 concentration and air humidity

Average daily concentrations were determined in order to obtain regularities in PM10 concentrations distribution on an annual basis. The dynamics of average daily PM10 values in the studied period (March-December) is presented in figure 5. Although the conclusions are somewhat limited due to the lack of values for January-February, there are certain seasonal patterns of changes in the average daily of PM10 concentration values. Hypothesis by analogy with figure 3 – an increase in concentration is associated with a decrease in air temperature, a decrease – with an increase. The regularity can be observed both during the day (temperatures are always lower at night than during the day) and throughout the year (in cold periods, the concentration of particles is higher).

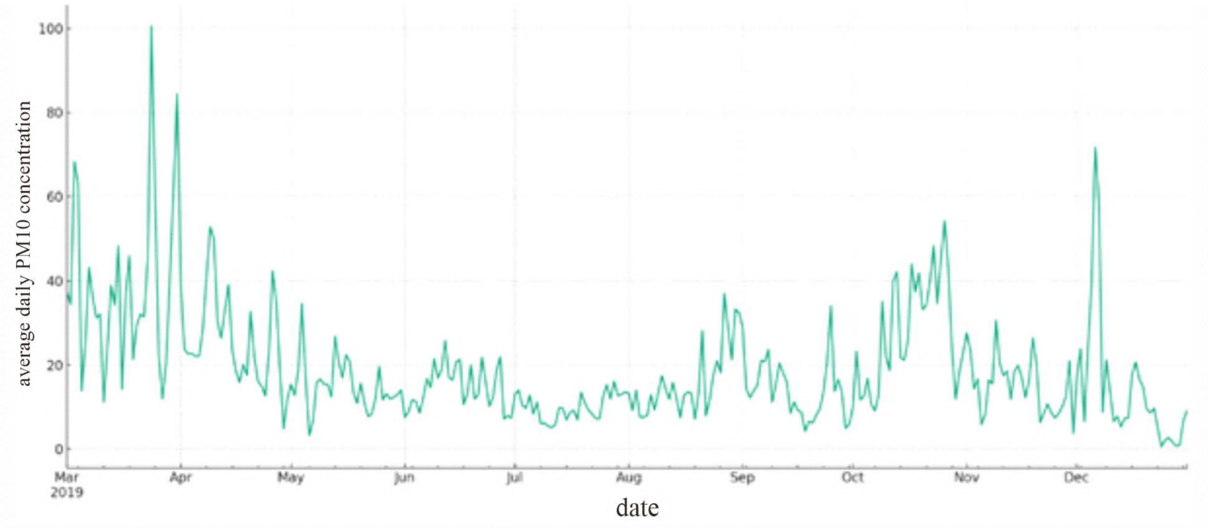

Figure 5. Dynamics of average daily PM10 concentration values.

In figure 5, significant fluctuations in daily concentrations (from 0 to 100 μg/m^3) can be observed, especially in the cold period of the year. The highest average monthly values of PM10 are in March, the lowest are in July. With the average daily limit value of 50 μg/m^3 in force in Ukraine and the EU, the number of exceedances is 442 instantaneous values. According to EU standards, no more than 35 average daily exceedances per year are allowed.

The established patterns are probably related to a number of factors, such as meteorological conditions, sources of pollution or chemical processes in the atmosphere. For example, in the colder months, the use of heat energy increases, in particular by burning solid fuel in the city's boiler houses, which leads to an increase of solid particles concentration. The heating period in Ivano-Frankivsk lasts on average from the second decade of October to the second decade of April. Also, in the cold period, humidity is usually higher and the air can be more stable, which makes it difficult for pollutants to disperse.

To test the hypothesis of the dependence of the solid particles concentration on the air temperature, to establish seasonal features and relationships, the average monthly and average weekly PM10 concentration and the average monthly and average weekly air temperature were calculated. The obtained results are presented in figure 6.

Visually, it can be assumed that there is an inverse correlation between temperature and PM10 concentration, especially in colder months: PM10 concentration is usually higher at lower temperatures.

The mathematical relationship between the average monthly PM10 concentration and the average monthly air temperature is described by the equation:

$$\mathrm{PM10} = -0.5914 \cdot t + 27.6082 \tag{4}$$

where PM10 – PM10 concentration (μg/m^3), t – temperature, $^{\mathrm{o}}$C.

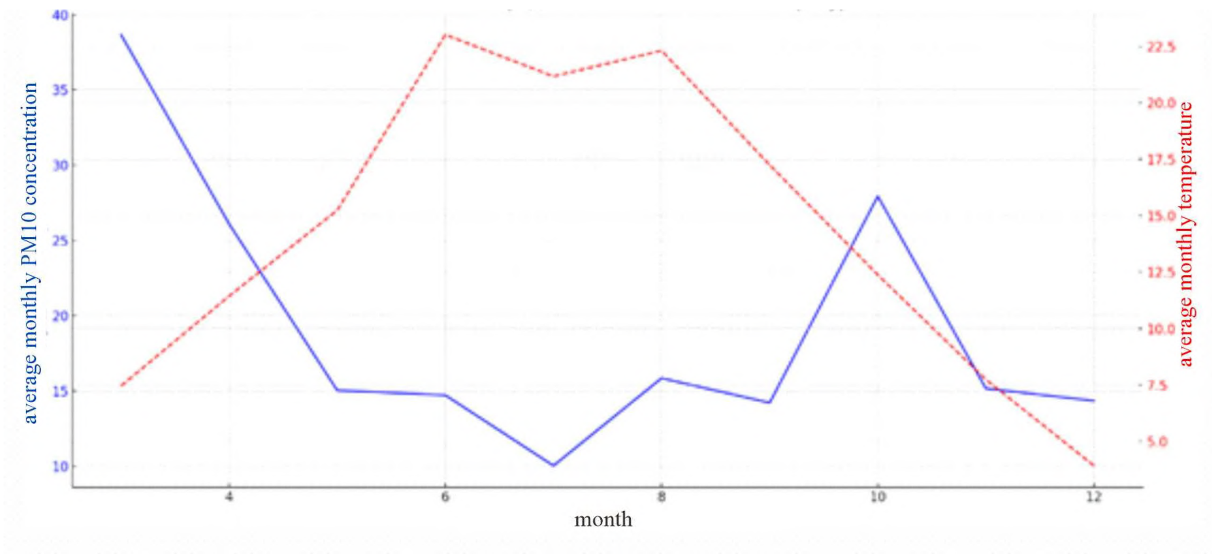

Figure 6. Dynamics of average monthly values of PM10 concentration and air temperature.

The coefficient of determination R^2 for this model is approximately 0.20, which indicates a low degree of connection between temperature and PM10 concentration for average monthly indicators.

Linear regression was also used to find the mathematical relationship between the average monthly values of PM10 concentration and air humidity. The mathematical relationship between values is described by the equation:

$$\mathrm{PM10} = -0.8274 \cdot h + 95.5097 \tag{5}$$

where PM10 is PM10 concentration (μg/m^3), h – relative air humidity (%).

The coefficient of determination R^2 for this model is approximately 0.51, which indicates a moderate relationship between humidity and PM10 concentration for monthly averages.

To test the hypothesis about the joint effect of factors on PM10 concentration, multivariate linear regression was used to find the mathematical relationship between the average monthly values of PM10 concentration, air humidity, and temperature, which is described by the equation:

$$\mathrm{PM10} = -0.7963 \cdot h - 0.5322 \cdot t + 100.1946 \tag{6}$$

where PM10 – PM10 concentration (μg/m^3), t – temperature, $^{\mathrm{o}}$C, h – relative air humidity (%).

The coefficient of determination R^2 for this model is approximately 0.67, which indicates a significant moderate relationship between the specified parameters and PM10 concentration for average monthly indicators.

A higher coefficient of determination compared to previous univariate regressions may indicate that the combined factors (humidity and temperature) together better explain the variability of PM10 concentration.

This confirms the hypothesis that t PM10 concentration in the atmospheric air of Ivano-Frankivsk city depends on a set of meteorological parameters, the main ones of which, as we proved in the conducted research, are the atmospheric air temperature and the air relative humidity.

The 3D image (figure 7) illustrates the dependence of the average monthly PM10 concentration on humidity and air temperature.

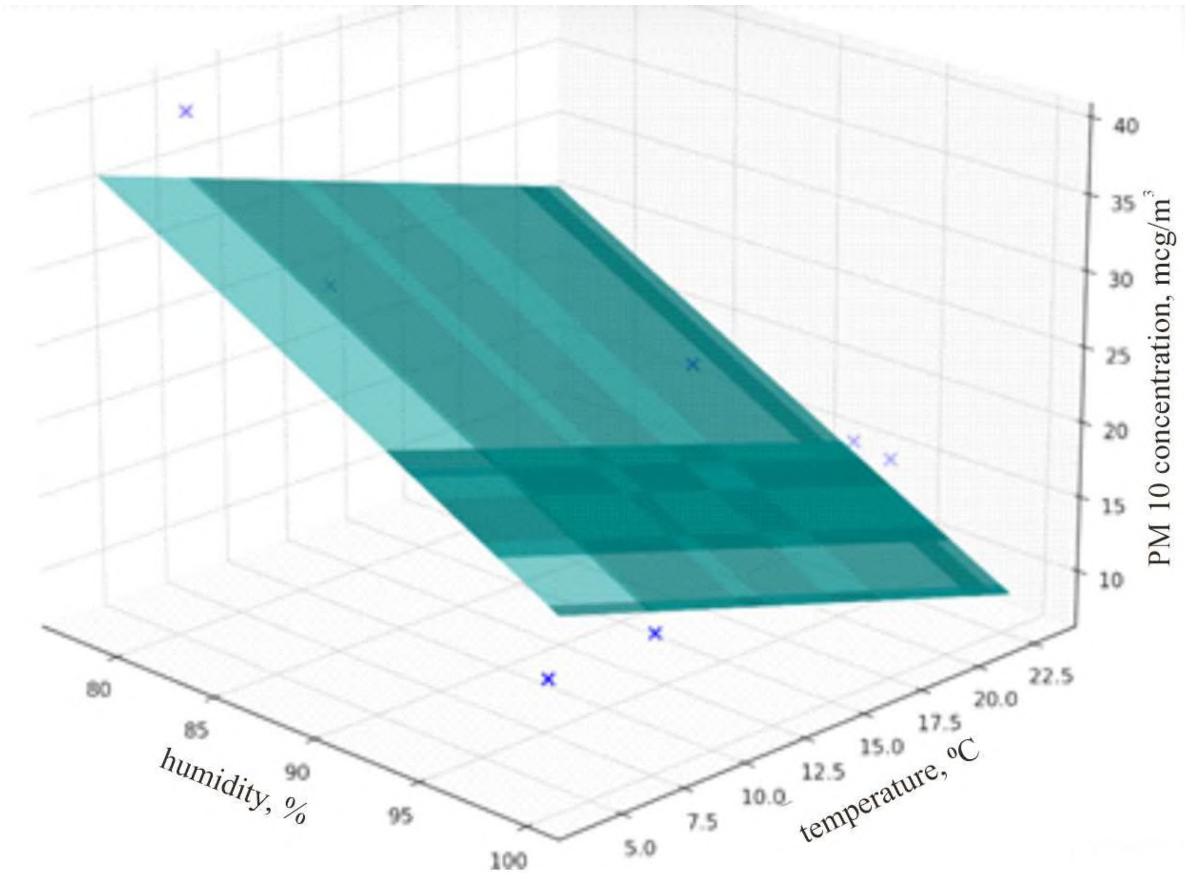

Figure 7. Dependence between average monthly values of PM10 concentration, temperature and air humidity (blue crosses – real data, blue surface – predicted plane based on multivariate linear regression.

To confirm the importance of the coefficient of determination R^2 (0.67), Fisher's test $F = 70.95$ (more than critical) and mean square error MSE = 23.12 were calculated. On the basis of this, it can be stated that the model is acceptable for estimating and forecasting temporal patterns of PM-10 solid particle concentration in the atmospheric air of Ivano-Frankivsk city, depending on the average monthly indicators of humidity and atmospheric air temperature.

5. Conclusions

In the article the database of the public air quality monitoring station in the central part of Ivano-Frankivsk is analyzed and the mathematical dependence for assessing and predicting the time patterns of PM10 particle concentration in the atmospheric air of Ivano-Frankivsk depending on the average monthly humidity and temperature is proposed. The main conclusions are as follows:

1. In the daily variation of PM10 concentration, a decrease in concentration is observed from a maximum of about 0:00 to a minimum of about 16:00 (with an intermediate increase and stabilization at 10:00-11:00). The proposed sinusoidal model reflects the distribution of data in the morning, from 5 to 11, quite well.
2. The seasonal variability of PM10 concentrations is characterized by higher values in the

cold season (the highest monthly average PM10 values are in March, the lowest in July). However, there are significant fluctuations in average daily concentrations (from 0 to 100 μg/m^3), especially in the cold season. 442 instantaneous indicators are above the normal daily average limit value of -50 μg/m^3.

3. There is a relationship between PM10 concentrations and air temperature both during the day (nighttime temperatures are always lower than daytime temperatures) and during the year (higher particle concentrations during cold periods).
4. The assumption of the joint effect of air humidity and air temperature on PM10 concentration is confirmed by the regression equation between the average monthly values of the parameters: $PM10 = -0.7963 \cdot h - 0.5322 \cdot t + 100.1946$. The values of statistical indicators ($R^2 = 0.67, F = 70.95$, MSE $= 23.12$) indicate that the function is acceptable for assessing and predicting the temporal patterns of PM10 particle concentration in the air of Ivano-Frankivsk depending on the average monthly humidity and the atmospheric air temperature.
5. The identified daily and seasonal patterns are likely related to such factors as meteorological conditions, pollution sources, or atmospheric chemistry, which requires further investigation. And the identification of the relationship between the total impact of meteorological factors on the PM10 concentration can be used to adjust management decisions to monitor and improve air quality in the city.

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The application of remote monitoring tools in the educational process on the example of the research of the content of water vapor in the atmosphere

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The application of remote monitoring tools in the educational process on the example of the research of the content of water vapor in the atmosphere

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Abstract. The paper shows the advantages of using remote satellite monitoring of the Earth in the educational process for the purposes of sustainable development. Using the example of the study of water vapor content in the atmosphere of Ukraine from 2001 to 2022, calculations of two approaches to obtaining, processing, and interpreting remote sensing data are given. The first approach – complicated – consisted of receiving satellite monitoring data and their further processing (transformation, cutting within the given area, interpretation, and conversion) in the Erdas Imagine program directly on a local computer. The second approach – simplified – consisted of the application of the Giovanni NASA online web application, which allows effective use of remote satellite monitoring data on a remote server based on specific requests and configured parameters, with results displayed on the screen in the form of thematic maps and graphs, that is, requiring their processing to a minimum. The discussion provides a comparison of the obtained results of these two proposed approaches (complicated and simplified) and describes their advantages and disadvantages for more efficiently obtaining the results of scientific research.

1. Introduction

In the last decade, the problem of modernizing the education system and ensuring its high quality was at the center of attention in Ukrainian society. The education of schoolchildren acquires new characteristics thanks to the availability of information technologies, and the emergence of an informational educational space and environment, which is necessary for self-development and self-improvement. A developed intellect, the ability to competently work with any information, and a generally high level of information culture are the most important characteristics of a person adapted to life in modern society.

Modern higher education is characterized by an active transition to the use of new information technologies. In the educational process, informatization programs are implemented, electronic textbooks are developed, and distance learning technologies are developed [1]. All this is due to the fact that a graduate of a higher professional education institution must be ready to work with ICT. Such skills will be needed when solving professional tasks. Adhering to modern trends, employers set higher requirements for future professionals.

Geoinformation technologies are technologies and systems that allow the user to work with spatial data, build models, and solve tasks of spatial and temporal analysis. In the same context, the term geoinformation systems can be formulated – these are systems whose task is the collection, storage, and analysis of spatio-temporal data, as well as their graphic visualization. Today, GIS is used to understand both software and application packages that allow the processing of spatial data [2]. The implementation of these technologies in the system of geographic education is based on the use of GIS – geoinformation systems [3, 4].

The use of information technologies in the natural sciences makes it possible not only to verify information but also, based on the concept of scientific education, to acquire a new, own system of knowledge and ideas about how our planet "works" and how we influence it. Today, anyone can get access to satellite Earth observation data. The space image contains a large array of information, which can be seen and analyzed through the use of a number of special software tools. Currently, there is a large amount of such software in the world, which is created both on a commercial basis and with open-source software. This publication focuses on using Giovanni. It is one of the well-known functional resources that are freely available, dynamically developing and used internationally in academic and professional environments.

The combination of remote sensing with geoinformation systems made it possible to explore the Earth's surface in a new way [5]. The accuracy and information content of remote sensing data is constantly improving due to the increase in the resolution of satellite images and the number of channels, the spectrum of the survey can show detailed information about the level of various objects. Satellite imaging allows not only to obtain images of the Earth's surface and calculate various spectral indices from them but also to obtain maps of geophysical indicators of the state of the environment on a planetary scale using various climatic, hydrological, chemical, and other models in combination with ground data from monitoring stations.

2. Literature review

The practice of using materials of remote sensing in research projects of students of general educational institutions and students in higher education exists and is described in many scientific and methodological works. Namely, as Voss et al. point out [6], the use of remote sensing in school education is reduced to the visual presentation of satellite images to students in lessons, therefore the need to develop educational and methodological literature and didactic teaching aids is necessary to improve the literacy of students and retrain teachers in this direction. The results of an online survey of teachers of geography in Northern Ireland, as stated in [7], indicate that, in general, teachers positively perceive GIS as a tool that can be used in the educational process, express a desire to receive additional materials and undergo training in this direction. In Norway, Rød et al. [8] concluded that the gradual implementation of GIS in school by geography teachers should start with web applications based on GIS or free viewing programs, in particular satellite images. For example, in the publication [9], a broad international view on the pedagogical value of GIS technologies in school was collected and it was demonstrated that GIS is not only a technological tool that should be used in school but also a catalyst for motivation, encouragement and cooperation in understanding and solving global problems. Students should have the opportunity to independently investigate the chosen scientific problem so that their educational experience is real and useful, and the introduction of GIS and remote sensing technologies into the educational process contributes to the performance of such research. Similar reviews were also conducted by Ukrainian scientists, in particular in the work considered the implementation of GIS in the geography course of a specialized school [10, 11]. The analysis of scientific and pedagogical literature showed that in Ukraine, at present, the implementation of GIS and remote sensing technologies in the practice of school education is just beginning.

The educational experience of using materials of remote sensing in higher schools is described in such works. Hejmanowska et al. [12] on the example of the use of satellite images in higher educational institutions, it is assumed that the use of GIS and remote sensing technologies forms a scientific type of thinking in the student. The development of educational electronic materials on the use of remote sensing of the environment is presented in the work [13]. Enhancing visualization techniques with a digital AR application called Satellite Skill 5 helps users conceptualize the theory and technology of remote sensing by demonstrating the potential of datasets such as multispectral imagery, SAR backscatter, drone orthophotography, and bathymetric LIDAR to solve real-world problems, with examples solving many issues of UN sustainable development. The goals (SDGs) are given in the work [14]. Electronic learning of photogrammetry, remote sensing, and spatial informatics is discussed in the paper [15] which emphasizes that GI-Science achievements for the natural and anthropogenic environment help to improve the quality of life. Learning through education must match these achievements. The work deals with training in the field of remote sensing and Internet technologies [16]. The authors of the work present their vision of the application of the geoinformation system in education [17–19]. The importance of teaching geographic information systems at universities in the process of building a European society based on knowledge is shown in the work [20].

A lot of researchers use Giovanni, a web-based application of the NASA Goddard Earth Science Data and Information Services Center (GES DISC) Distributed Active Archive Center (DAAC). Giovanni is a tool for science education. Lecturers at the University of Plymouth (UK), the University of South Carolina (USA), and Bigelow Laboratory for Oceanic Sciences (Maine, USA) have described Giovanni as a very useful tool for their educational activities, and at Plymouth University they call Giovanni a research tool that allows students to explore the regions and processes of their interest with great ease. At the University of South Carolina, training involved generating specific types of Giovanni output for specific regions to illustrate oceanic processes in those regions. In all cases, lecturers noted that the ease of use of the program and the opportunities it provides to students with limited computer experience were an indisputable advantage. The experience of these universities indicates that Giovanni can easily be added as a research tool to oceanographic classrooms. In the early months of 2007, the US Naval Academy (QUSNA) Remote Sensing Class participated in initial pedagogical testing of the use of Giovanni in oceanographic education. First, the students took an oceanographic "knowledge test" consisting of questions that could be answered using Giovanni, and then they were shown an interactive lecture using Giovanni. After the demonstration, the students briefly described their impressions of the system and their expectations from it. After the demonstration, the lecturer created a collaborative research project using Giovanni as a research tool. After the research project presentations, students were shown how to use Giovanni to answer survey questions, and all students answered more survey questions correctly after using Giovanni. At the end of this exercise, students completed a short survey about their use of Giovanni and rated their expectations. All students reported that Giovanni met or exceeded their expectations for ease of use and visualization and analytical capabilities [21]. Acker et al. [21] also describes the benefits of using Giovanni in high school study of environmental science to study regional climate change, compare oceanic regions, and determine how much rain tropical storms contribute to the annual precipitation of a selected region.

Giovanni is a well-known tool for scientific research, since its launch, more than 1700 articles on Giovanni have been published in peer-reviewed scientific journals. In particular, a large number of works highlight the results of the analysis of air quality, the nature of wind for wind energy, the relationship between weather and human health, monitoring the impact of agriculture, the correlation of algae blooms, etc.

Based on the relevance of the study of the use of remote sensing for educational purposes and the analysis of international experience, the **problem** stated in this article is the possibility of using two approaches to the processing of remote sensing data in the educational process.

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The **purpose** of this research is to compare the implementation of two approaches: complicated, which requires downloading and processing data in specialized software, and simplified, automated study of one of the applied problems using remote cloud resources, namely the study of the water vapor content in the atmosphere.

The **object** of the research is complicated and simplified approaches to the processing of data of remote sensing.

The **subject** of the study is the monitoring of the water vapor content in the atmosphere over the territory of Ukraine from 2001 to 2022 using the two approaches.

The **task** of the research – is to assess the skills and abilities of pupils and students necessary for the implementation of two approaches.

3. Methodical approaches

For a deeper understanding of natural processes, we considered two approaches to working with remote sensing data. *I approach (complicated)* is an approach, where the researcher has to: 1) Use the Internet or other primary data, establish which data from which satellites are needed for the research, and 2) find sites with an archive of information on remote sensing data. (Usually, climatic data are never in the same archive with data of high and medium spatial resolution), 3) via the Internet to receive the selected files for the study area on a personal computer, 4) to find software that will be able to open the input files without error and convert them, taking into account the storage features, into a convenient and familiar data format for a scientist. (For example, climate data can be in *nc*, *hdf*, *csv*, or other formats, while optical multichannel data is usually in *tif* format for each channel separately), 5) conducting a direct study with transformed input data and obtaining a result (in the study, an example of using a software product for processing remote sensing data – Erdas Imagine will be shown).

The Erdas Imagine program is one of the well-known software complexes for processing remote sensing data, which allows you to open data in various formats, perform their radiometric and spatial correction, calculate various indices, perform image classification, etc. The program has the ability to create your own models, which can consist of various raster data (satellite images, topographic maps, digital relief models, etc.) and vector data (contours of administrative areas, elevation isolines, etc.), which allows solving various problems facing researchers.

Using the Erdas Imagine program, data processing consists of the following steps: 5.1) Receiving input data in *csv* format and converting it to *grd* format using a developed program that adds additional information about the total number of columns and rows of the image, as well as latitude coordinates and longitude; 5.2) Using the space image processing program Erdas Imagine, input data from *grd* format to *img* format was converted using the *Import* function; 5.3) Multi-channel images containing data from January to December were created for each year using the *Layer Stack* function; 5.4) Using the *Model Marker* function of the Erdas Imagine program, the average values of water vapor for each year were calculated; 5.5) The territory of Ukraine was selected using a vector layer from the "Ukraine 500" map using the *Subset* function; 5.6) The UTM / WGS84 coordinate system was established using the *Reproject* function of the Erdas Imagine program. The validity of using the complicated approach is confirmed in the works of [22–24].

Data from the Terra/MODIS satellite, namely, the MOD07 product, were used as input values for the *I approach* for the diagnostic assessment of the water vapor content over the territory of Ukraine. The study used 264 images of monthly values of water vapor concentration for the years 2001-2022 [25]. The input data processed according to the method made it possible to obtain the averaged distribution for the period 2001–2022 and plot changes in water vapor over 22 years. The ArcGIS program was used for the visual design of the drawings with the addition of geographic coordinates, scale, and legend.

II approach (simplified) – has a significant difference from the first, to achieve the result,

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the scientist does not need to perform points 1) – 4) of the previous method. The researcher immediately conducts research using a web platform or an online application, which provides him with a simple and intuitive way to visualize, analyze, and access huge volumes of remote sensing data of the Earth, without downloading them directly to a computer for processing (for example, the use of the Giovanni online application is given).

Giovanni (Geospatial Interactive Online Visualization and Analysis Infrastructure) is a web application developed by NASA's Data and Information Services Center (GES DISC). Giovanni is one of the pioneering web services available to the public to analyze NASA Earth data. Since 2003, Giovanni has provided users, both novice and expert, with a way to use remote sensing data and model that data with a minimal investment of time and software. Scientists and educators note the ease of use of Giovanni. This resource provides a way to find data from more than 1600 geoscientific variables (information about weather, climate, atmospheric composition and dynamics, oceanography, hydrological processes and interactions of Earth systems, etc.) of interest to a wide range of research fields, and serves as a reference an environment for finding topics of scientific research. Giovanni consists of the following main elements: an interactive map for selecting the research area; a menu of available data products; a calendar menu for choosing a time period; a visualization options menu; visualization-specific options (color palette, axis values); output options menu.

The data with which the web application allows you to work have a low spatial resolution – from one to tens of kilometers due to the complexity of modeling such data and their significant dependence on the ground observation network. At the same time, the frequency of shooting is usually quite high – once a day, which allows for effective use of this data by services for monitoring natural processes and warning about emergency situations. Giovanni allows researchers to quickly explore data, and most importantly, the data can be analyzed directly online before downloading high-resolution input data.

To use the Giovanni web application, researchers need to take the following steps: 1) Register on the Giovanni website (`https://giovanni.gsfc.nasa.gov/`); 2) Selecting the indicator that we need to investigate, namely Water Vapor, for this on the Select Variables panel, select Atmospheric Chemistry (Chemical components of air); then under the keyword Water Vapor in the new list that will appear in the window, select Precipitable Water Vapor (IR Retrieval) Total Column: Mean of Level-3 QA Weighted Mean (MOD08M3 v6.1); 3) Select the study range (year/month/day), the selected Precipitable Water Vapor data is available from the middle of 2002 to present. In the Select Date Range (UTC) field, select the period for which the program should generate an averaged map, namely from 2003 to 2022; 4) Select the display format of the research result in the Select Plot field. Below are three ways to display Time-Averaged Map data. Area-Averaged Time Series and Time Series, Recurring Averages; 5) Selection of the research area: in the Select Region (Bounding Box or Shape) line, draw a rectangle within Ukraine on the map. The program can process the research territory – within the state borders of the country or any rectangular or square shape specified by the user; 6) Finally, press the Plot Data button to display the data. The obtained results in the form of a map on the graph can be saved to the computer as an Image or downloaded in Microsoft Excel format.

Data from the TERRA/MODIS satellite was used as input values for the II approach for the diagnostic assessment of the water vapor content over the territory of Ukraine, namely, the MOD08 product, which is sorted into cells 1 by 1-degree equiangular grid, which covers 24-hour interval, and then summed worldwide.

4. Results

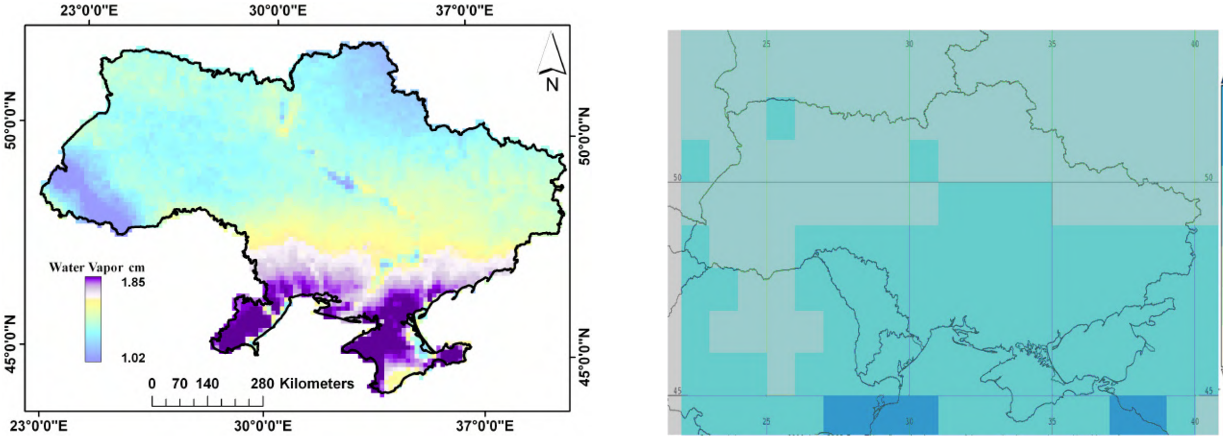
The content of water vapor in the atmosphere over the territory of Ukraine was taken as an example of the study to establish its contribution to the warming process.

In recent years, the increase in surface temperature has been an indisputable fact, but the mechanisms that contribute to global warming remain unclear, and it is becoming increasingly important to explain their respective effects on air temperature rise. Despite the obvious influence of natural mechanisms of climate formation, many researchers (for example, the Intergovernmental Panel on Climate Change) call the increase in the content of greenhouse gases CO_2 and CH_4 the main mechanism of modern warming of the global climate. Although increases in carbon dioxide and methane may be a source of increased greenhouse effect and therefore global warming, the role of the most important molecule in our atmosphere, water, is rarely discussed. Water vapor is not only the main greenhouse gas on Earth. Due to the release of latent heat during condensation, it also plays an active role in the dynamic processes that shape the global atmospheric circulation and thus the climate. Scientific research on the role of water vapor in global and regional weather processes is evidenced by the following studies. The effect of water vapor on climate change depending on altitude is shown in [26]. The researchers discovered the dependence of climate change on water vapor, due to which the temperature trend first increases at low specific humidity, and then decreases with increasing specific humidity. At ground level, the maximum trend of temperature change is manifested in the range of specific humidity of 2.0–3.0 g/kg. This suggests that water vapor is a mediator of climate change and may be responsible for altitude-dependent climate change. The study [27] used the Global Land Data Assimilation System (GLDAS) datasets and the National Oceanic and Atmospheric Monitoring Laboratory (NOAA) (GML) data to investigate the spatiotemporal characteristics of global warming and its driving mechanisms. The effects of water vapor, radiation (total long-wave radiation), and CO_2 on temperature rise are quantified in terms of a coupled land–atmosphere system, and water vapor is characterized by a vapor pressure deficit (difference between saturated and actual water, vapor pressure) to characterize its impact on the global water-heat cycle. The results show the following: Under significant global warming, the vapor pressure deficit (VPD) shows an increasing trend, which is explained by the fact that the rate of increase of actual water vapor is relatively slower than that of saturated water vapor; compared to the significant positive contribution of water vapor to global warming, CO_2 is not, as commonly expected, the most critical greenhouse gas causing global warming; water vapor and total longwave radiation (NLR) have significant mutual feedback on global warming. Changes in projected atmospheric water vapor in Central Asia using several models from CMIP6 are shown in [28]. The response of stratospheric water vapor to climate change caused by various influencing factors is shown in [29–33]. The relationship between extreme precipitation and water vapor in the current climate and the consequences are investigated in [34]. The variability of water vapor in the tropical middle atmosphere, observed from satellites and interpreted using SD-WACCM simulations, is shown in [35].

Based on the analytical review, it can be concluded that water vapor is the dominant greenhouse gas, the most important gaseous source of infrared opacity in the atmosphere. As concentrations of other greenhouse gases, particularly carbon dioxide, increase due to human activity, it is extremely important to predict how this will affect the distribution of water vapor. As the concentration of water vapor increases in a warmer environment, the climatic effects of other greenhouse gases will increase. This is important positive feedback that increases the sensitivity of surface temperature to carbon dioxide by nearly a factor of two when considered in isolation from other feedbacks, and perhaps by a factor of three or more when considered in interaction with other feedbacks [36, 37].

Model projections for future high-emission scenarios show a significant increase in atmospheric water vapor, approximately twice the current value by the end of the 21st century [38]. This is a serious concern for the global and regional climate, as the increase in water vapor volumes will further increase global warming [39, 40]. Thus, significant increases in water vapor in the troposphere at high latitudes and high altitudes may further increase global temperatures and thus accelerate global climate change.

We present the results of calculations of the concentration of water vapor according to the I and II approaches (figures 1 and 2).

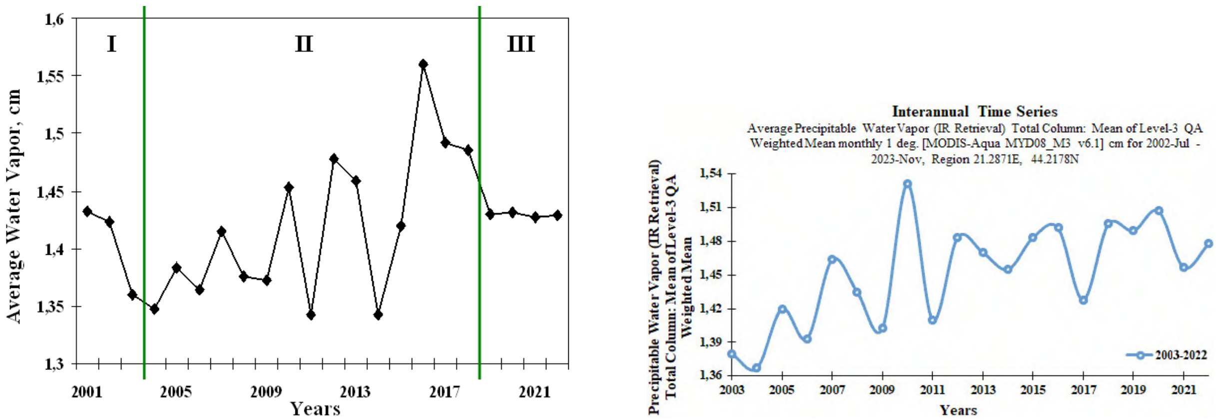


(a) (b)

Figure 1: Average distribution of the amount of water vapor over the territory of Ukraine according to data from the TERRA/MODIS satellite: a) during 2001 – 2022 (*I approach*), b) during 2003 – 2022 (*II approach*).

The analysis of the constructed map of the distribution of water vapor concentration according to the I approach (figure 1.a) showed that within the territory under study, a reduction in the amount of water vapor in the atmosphere in the direction from south to north is evident. The maximum values of water vapor retention were established in the south of Ukraine – in the Crimea, the Black Sea Basin, and adjacent areas. This area is characterized by the highest air temperatures compared to the rest of the area. However, this area directly borders the Black and Azov seas, from the surface of which there is intense evaporation. According to the nature of the distribution of values of the amount of water vapor in the atmosphere on the territory of Ukraine, two large regions, the Northern and the Southern, are confidently distinguished. The border between them is quite clear and runs approximately the width of the city of Kropyvnytskyi, including the Donbas region. In addition, in the west of the territory, there is a relatively small Western region located in the Carpathian region, which differs significantly in values. The northern region is characterized by low variability of the amount of water vapor in the atmosphere, the content of which is characterized mainly by average values. This is in good agreement with the relatively homogeneous natural conditions within this area. Within the Southern region, the water vapor content in the atmosphere varies widely, from minimum to maximum, and the areas occupied by different values of vapor content are relatively small in size. This is due to the influence of the seas and their complex coastline. As you move away from the sea coast, the water vapor content changes significantly less. The western region is characterized by minimum values of water vapor content. At the same time, they vary little by area, this is the most stable area in terms of water vapor content. Perhaps this is because only a relatively small part of this area is located in the territory under study. The highlighted areas differ from each other in terms of the absolute features of the relief and the size of the areas occupied by water basins, that is, those factors that have a decisive influence on the distribution of temperature in the atmosphere. Smaller formations stand out within the Northern and Southern regions. The territory of the Northern region is divided by the Dnipro River valley into the western and eastern halves. This is even though the Dnipro valley is relatively small in size, taking into account the size of the pixels used for observations. In general, the Dnipro River valley differs from the surrounding area both in terms of the intensity of observed water vapor content values and the sharp variability of values within this area. This is probably caused by a much higher moisture content in the river valley than in the surrounding area. As well as the presence of separate significantly watered and drained areas. In the western half of the Northern region, in the northwest of the territory of Ukraine (region of the Ovrutsky uplift), there is a fairly significant area with increased values of water vapor content and an area located to the south with reduced values of water vapor content in the atmosphere. In the eastern half of the Northern region, significant volumes of the area of reduced values of moisture content were recorded, which can be traced far beyond the borders of Ukraine. The southern region differs from the northern region in the less uniform distribution of vapor content. In the north of the region, approximately to the latitude of the Kakhovsky Reservoir, the territory is characterized by relatively high-water vapor content compared to average values. A very colorful picture is observed to the south. This is not surprising; it is caused by the influence of both the land and the Black and Azov seas. The valley of the Dnipro River stands out within the southern region, but, unlike the Northern region, these two territories do not differ from each other.

The analysis of the map of the distribution of water vapor over the territory of Ukraine according to the II (simplified) approach (figure 1.b) is less detailed, according to it, two large Northern and Southern regions are also distinguished, but it is not possible to distinguish local (more detailed) differences within these two regions.



(a) (b)

Figure 2: The schedule of changes in the amount of water vapor over the territory of Ukraine during 2001-2022 according to data from the TERRA/MODIS satellite: a) according to the *I approach*, b) according to the II approach.

The constructed graph of changes in the amount of water vapor over a multi-year period for the I approach (figure 2.a) indicates significant changes in the water vapor content in the atmosphere in different years and at the same time, allows us to identify three cycles of changes in the water vapor content for the territory under investigation. These are the following cycles: the end of the I cycle: 2001 – 2003, where a drop in the amount of water vapor is observed, the II cycle: 2004 – 2018, where a trend of increasing the amount of water vapor is observed, and the beginning of the III cycle: 2019 – 2022, where an almost constant increase is observed the amount of water vapor. Cycle 2, covering the years 2004-2018, was best shown on the available materials. It is characterized by a regular increase in water vapor content. The other two cycles, represented by a limited number of observations, are largely conditional. The greatest interest is cycle 3, which is characterized by an almost constant amount of water vapor in different years, which was not observed in other cycles. In addition, the water vapor content in this cycle is close to the 2001 content.

For the II approach, the constructed graph (figure 2.b) of changes in the water vapor content in the atmosphere of Ukraine is characterized by a constant fluctuation of minimum and maximum values, peak values are less prominent, but a trend toward an increase in the water vapor content in the atmosphere is visible. Although the two graphs have a lot in common, Thus, the years in which the minimum values of water vapor are recorded coincide on both graphs: 2004, 2006, 2009, 2011, and 2014, respectively, the years for the maximum values also coincide: 2005, 2007, 2010, 2012, and 2016.

As a result of the implementation of both approaches to the research of water vapor, we compiled tables of the possibilities of implementing these technologies into the educational process. Based on the obtained results (table 1), it is worth noting that the implementation of the first approach requires a significantly larger number of conditions and criteria, which is why the second approach is more of a priority for secondary education, and the first approach is suitable only for senior students of higher education and expert scientists, as it requires much more knowledge and time for its implementation and interpretation of the results obtained.

Table 1: By comparing the necessary conditions for the implementation of the two approaches.

Conditions or features of implementation of the approach in the educational process)	I approach (complicated) based on desktop software Erdas Imagine	II approach (simplified) based on the remote cloud resource Giovanni
availability of training instructions	−	+
the need for initial knowledge of the basics of remote sensing	+	−
availability of a powerful personal computer	+	−
the need to install specialized software	+	−
the need to download and perform preliminary processing of input data of remote sensing	+	−
using a large amount of time for data selection and process implementation	+	−
obtaining the result in the form of statistical graphs directly in the program	−	+
the possibility of simultaneous comparison of various thematic data	+	+

5. Discussion

It is possible to say that the complicated approach requires the researcher to have a lot of knowledge not only in the field of remote sensing but also in related sciences. The researcher must have full knowledge of satellite survey data, understand what problems can be solved, and have special software tools for processing satellite information. With the development of the latest technologies in the field of remote sensing, there is a shift away from direct processing of primary data and a transition to the use of products created from this data. The owners and developers of the MODIS spectrometer installed on the Terra and Aqua satellites were the first to start this trend. About 80 Terra/MODIS products are currently available, such as subsurface temperature, vegetation index, and others. This allowed researchers to use the indicators they needed without participating in their creation, which greatly expanded the possibility of applying remote sensing data in various fields. But all the same, such products also had to be found, downloaded, and processed on your personal computer.

Therefore, the proposed complicated approach may, due to the complexity of implementation and implementation of the result, be suitable only for students in senior years who have a basic level of knowledge of specialized universities. For pupils of secondary education, it is advisable to use a simplified approach. The great advantage of the simplified approach based on remote web portals is that data from different satellites, processed by the same algorithm, are concentrated in one place. This is a significant breakthrough in the possibility of using remote sensing data not only by information processing specialists but also by the general public of interested persons (schoolchildren, students, etc.). There are many satellite-based algorithms for measuring meteorological parameters, but not all algorithms can easily compare the products or analyze them with other relevant data. But Giovanni's methods illustrate how the data and visualization tools archived in GES DISC (Giovanni is a product of GES DISC) can be effectively combined with cloud computing and cloud-optimized data formats for effective climate analysis.

In general, the two considered approaches complement each other. A simplified approach provides a quick understanding of the process, while a complicated approach allows you to identify more detailed patterns of the process. All this ultimately improves the researcher's scientific results. The use of the Giovanni resource is aimed at the formation of pupils, students, and listeners of knowledge of the basics of remote sensing, skills of working with relevant software, its applications, and analytical tools, and involvement in search and research work.

In accordance with the set goal, the tasks of the program consist of the formation of pupils, students, and listeners of the following competencies:

- cognitive: formation of knowledge on the basics of remote sensing; development of geospatial and analytical thinking in pupils, students, and listeners; the ability to logically present one's thoughts and cartographically argue them;
- practical: formation of skills and abilities to create maps using space images and analytical tools in research activities; independent search and analysis of information; development of spatial thinking;
- creative: use of modern IT in education; formation of creative approaches in research activities and group work experience based on the project method;
- social: formation of a conscious, responsible attitude to the surrounding world, the ability to solve environmental problems; promotion of self-realization and professional self-determination of pupils, students, and listeners by means of GIS and remote sensing.

6. Conclusion

Modern education should be based on the search and application of the latest technologies that contribute to the development of basic competencies that form an independent and creative personality. In the future, this will open up prospects for the purposeful formation of competent specialists in various fields. Such a technology is the application of methods of remote sensing. The advantages of innovative methods of remote sensing are objectivity, reliability, comprehensiveness, detail, efficiency, periodicity, multi-spectral nature of observations, and, most importantly, multi-sectorality (the ability to solve multifaceted tasks in the monitoring mode).

The two methodological approaches considered in the work—complicated (with data processing on a personal computer) and simplified (with data processing on a remote server based on specific requests)—made it possible to conduct a comprehensive study of monitoring the content of water vapor in the atmosphere over the territory of Ukraine over a multi-year period of 22 years. The results of the study of the content of water vapor in the atmosphere showed that the changes are cyclical, and the data for 2022 corresponds to 2001.

As for the educational process, working with remote sensing data will teach them how to use diverse information in the form of space images.

Pupils and students will be able to: carry out operations with remote data, in particular, filter by dates and research area; to be able to search and select the most suitable types of remote sensing data for specific thematic tasks (in the context of climate change); use analytics tools; save the obtained results in the form of graphs and maps; to use the data of remote sensing in research works.

Competences will be formed among pupils and students: to use the materials of remote sensing in their research; use Giovanni software for remote data analysis; analyze the dynamics of changes in the atmosphere, hydrosphere, earth's surface, etc.; identify dependencies between processes (correlation, regression, etc.) based on satellite data.

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Below ground carbon stock of mangrove stands of a mining site in Hinatuan Island, Northeastern Mindanao, Philippines

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Abstract. Mangrove ecosystem provides important services such as storing and sequestering large amount of carbon. However, it faces several anthropogenic pressures especially from resource extractive activities that threatened the ecosystem. Hence, huge companies are obliged to make rehabilitation efforts to rehabilitate the mangrove ecosystem that they have caused damage. Our study aims to determine the carbon stock dynamics of a mangrove rehabilitated site which was damaged due to the siltation brought by the nearby mining. We established a study plot in a mangrove rehabilitated site (Lipata) near the mining area and on a nearby natural mangrove forest (cagutsan) as a point of reference. We determine the mean DBH, height and estimated the soil carbon storage capacities. We found out that in both sites of rehabilitated (Lipata) and natural (Cagutsan) mangrove stand the Rhizophora mucronata is the most dominant, both has similar mean dhb of 6 cm and the height is mostly dominated by. The soil C content shows that as the soil gets deeper up to 50-100 cm the higher the soil carbon content. There was no significant variation in terms of the average soil carbon content of the rehabilitated site is 42.63 MgC/Ha and the natural mangrove stand of 53.59 MgC/Ha. Hence the finding supports the effectiveness of the rehabilitation efforts and calls for continuous rehabilitation of damaged mangrove sites in the area.

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1. Introduction

The biodiversity of the Philippines is rich in both quantity and proportion. Because of its high endemism rates, varied ecosystems, and geographic isolation, it is recognized as one of the 17 mega biodiversity countries. Maintaining 5% of the world's flora, it ranks sixth internationally in terms of the number of plant species. The nation is home to about 65 species, or at least 50% of all mangrove species worldwide [1].

The diversity of mangroves is relatively high due its geographic location. The country holds at least 50% of the worlds approximately 65 mangrove species [2]. It is also considered as one of the top 15 most mangrove-rich countries in the world [3]. These mangroves are pivotal in supporting diverse marine life and providing essential ecosystem services, including coastal protection and carbon sequestration [2]. Mangroves, a resilient coastal ecosystem lining the interface between land and sea, are invaluable carbon reservoirs, pivotal in global carbon cycling and climate change mitigation [4]. Mangroves have a unique ability to sequester atmospheric carbon in their biomass and sediments, contributing significantly to reducing greenhouse gas concentrations [5, 6]. However, the perpetual and escalating threats posed by anthropogenic activities, particularly mining, cast a shadow over the stability of these ecosystems. As one of the most threatened and undervalued ecosystems globally, mangrove forests face considerable degradation, with estimates indicating a 30-50% decline in their extent. The vulnerability of mangroves to human-induced pressures underscores the urgency of investigating their carbon stock dynamics in regions undergoing mining activities [7].

The scenic Hinatuan Island, located in Taganaan, Surigao del Norte, boasts abundant mangrove forests that are integral to the livelihoods of local communities. However, due to anthropogenic activities as well as natural disturbances, it continues to lose its rich biodiversity resources including mangroves [3, 8]. This ecological wealth coexists with active mining operations, raising critical questions about the potential impacts on the carbon stock of mangrove stands. The delicate balance between economic development and environmental preservation necessitates a comprehensive understanding of how mining pressure influences the carbon sequestration capacity of mangroves in this unique island setting. Mining operations can cause significant alterations in the biophysical characteristics of mangrove ecosystems, such as changes in soil properties, hydrological regimes, and tree composition, which may affect carbon stocks [9]. Therefore, it is crucial to study the impact of mining activities on the carbon stock of mangrove stands to understand the implications for carbon sequestration and storage.

The research investigated the carbon stock dynamics of mangrove stands on Hinatuan Island under the influence of mining activities. This study aims to determine if there is a difference between the mangrove sites near and across the mining site on the belowground carbon storage capacity. We established sampling plots on a mangrove site with a mining operation and in a nearby natural mangrove forest. We determine the heterogeneity in vegetation in both sampling sites and estimated the average soil carbon. We hypothesized a difference in carbon storage between the two sites because the other mangrove sites were not disturbed, contrary to the mangrove in the mining site. Our study supports the broader call for mining site rehabilitation and protection of mangrove forests from further destruction to sustain roles in mitigating the impacts of climate change.

2. Methodology

2.1. The study area

2.1.1. Lipata in Hinatuan Island. Hinatuan Island is located in Barangay Talavera, Municipality of Tagana-an, Surigao del Norte Province, positioned at coordinates 9°46'09" N and 125°39'02" E. The island maintains an average annual temperature of 26.7°C and receives around 320 mm of precipitation annually. Its soil primarily belongs to the Ferralsols category, characterized by clay loam composition. The island's surface features nitrogen levels at 615

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cg/Kg, soil organic carbon at 1110 dg/kg, and maintains a pH level of 4.7 [10]. Spanning an estimated total area of 1,275 hectares, Hinatuan Island is significantly affected by mining activities, with 60% of its land covered by an approved Mineral Production and Sharing Agreement (MPSA 246-2007-XIII). Nickel mining operations have notably been active on the island since the 1980s.

2.1.2. Barangay Cagutsan. Barangay Cagutsan is situated within the City of Surigao, which is part of Surigao del Norte Province, located at coordinates 9°46'22" N and 125°42'04" E. Currently, the barangay encompasses about 12 hectares of mangrove forests. The prevailing climate in the area corresponds to type II based on the Corona classification system. The soil type in Barangay Cagutsan is classified as Histosols, primarily composed of organic materials. Histosols typically have limited drainage, which slows down the decomposition of plant and animal remains, leading to the accumulation of organic materials over time. The recorded pH level is 4.9, with organic soil carbon measuring 1084 dg/Kg, a bulk density of 68 cg/cm^3, and nitrogen content at 533 cg/Kg [10]. This natural mangrove forest, existing for around a decade, is under the protective oversight of the Department of Environment and Natural Resources (DENR) – Region XIII and the Local Government Unit of Barangay Cagutsan. Approximately ten years ago, the agency initiated the Assisted Natural Regeneration (ANR) program for this mangrove stand.

Five mangrove species were documented in both Lipata and Cagutsan area. Rhizophora apiculata emerged as the most dominant species in both sites accounting for 85.70% and 71.80%. the Lipata site has a total count of 175 individuals while the Cagutsan site has 206 individuals. The second most dominant species in Lipata is the Aegiceras coniculatum and is only recorded in Lipata. While in Cagutsan Rhizophora mucronata ranks second as the greatest number of individuals with Avicennia rumphiana species is found only in Cagutsan [11].

2.2. Field sampling design

In both the Lipata area, situated adjacent to a mining site, and the Cagutsan area, located at a distance from the mining sites, three (3) 150 m transect lines perpendicular to the beach was established, each spaced 50 meters apart. Within each 150 m line transect, two (2) 10 m × 10 m non-destructive quadrats were designated, hereafter referred to as zones, ensuring a 20 m gap between consecutive plots in figure 3.

Three parameters for each field plot were considered to estimate the soil carbon pool: (a) soil depth, (b) dry bulk density, and (c) organic carbon content (% Corg).

2.3. Soil carbon stock determination

Soil samples were randomly taken from the two sampling sites using soil corer of 100 cm high and 6 cm in diameter. Soil samples were partitioned into depth intervals of 0-30 cm, 30-60 cm, and 30-90 cm. Samples representing each depth were collected as subsamples. Collecting subsamples that represent a specific depth is more than adequate for mangroves, as the carbon content changes at a much slower rate with depth, making the collection of the entire range unnecessary [12]. Thus, subsamples obtained from each depth were utilized to analyze the soil carbon content. Soil samples were sent to laboratory for (Corg) using Walkley-Black Method.

The calculation of soil organic carbon per hectare was performed using the equation below [5]:

$$\text{Soil Carbon (Mg/Ha)} = \text{Bulk Density (g/cm}^3\text{)} * \text{Soil Depth Interval (cm)} * \%\ \text{Carbon content}$$

The calculation for the total soil carbon stock across the two entire sampling areas was derived using the equation below:

$$\text{Total Soil Carbon Stock (Mg)} = \text{Total Soil Carbon (Mg/Ha)} \times \text{Area (Ha)}$$

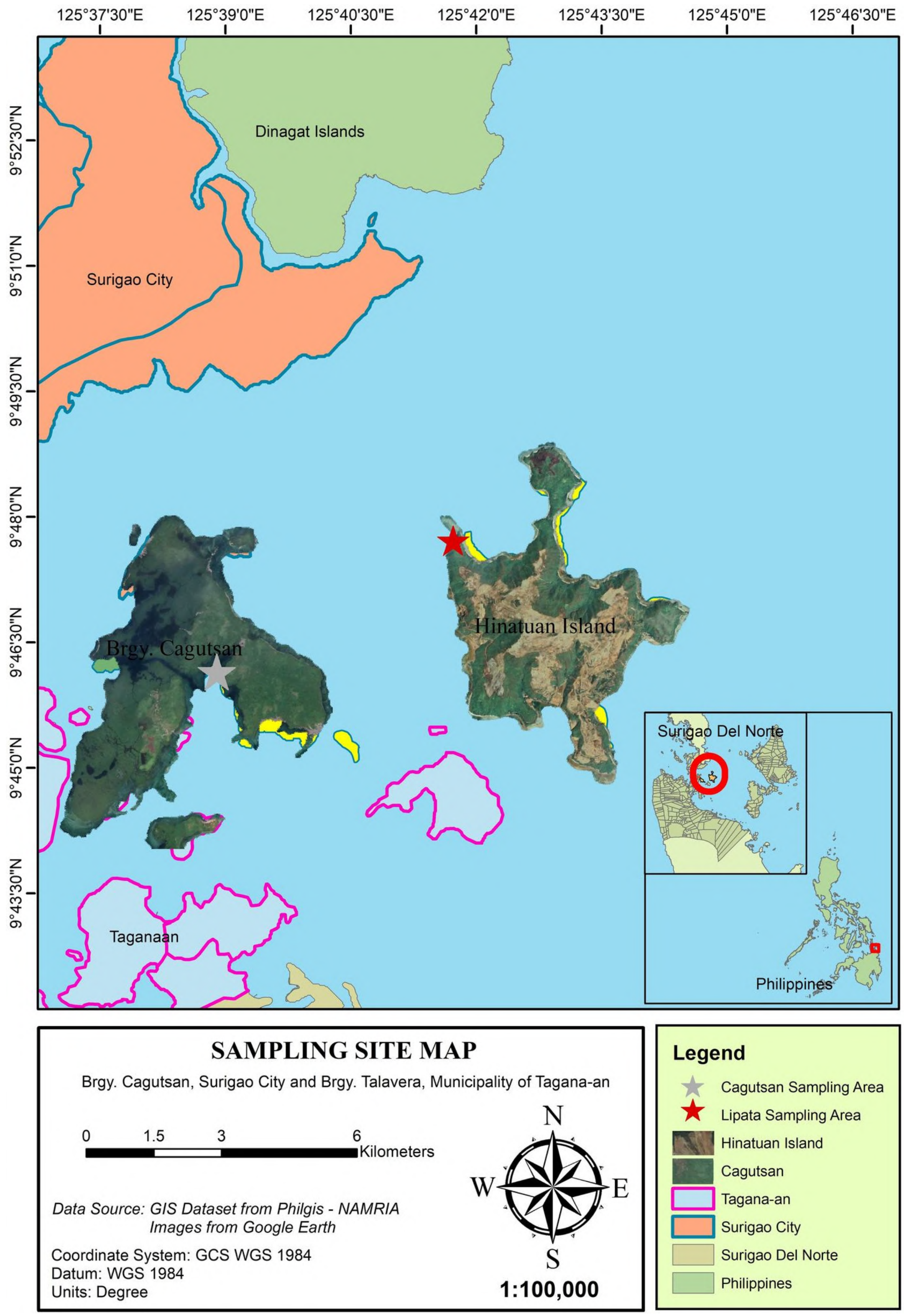

Figure 1. Map of Brgy. Cagutsan and Hinatuan island, Taganaan, Surigao del Norte, Philippines.

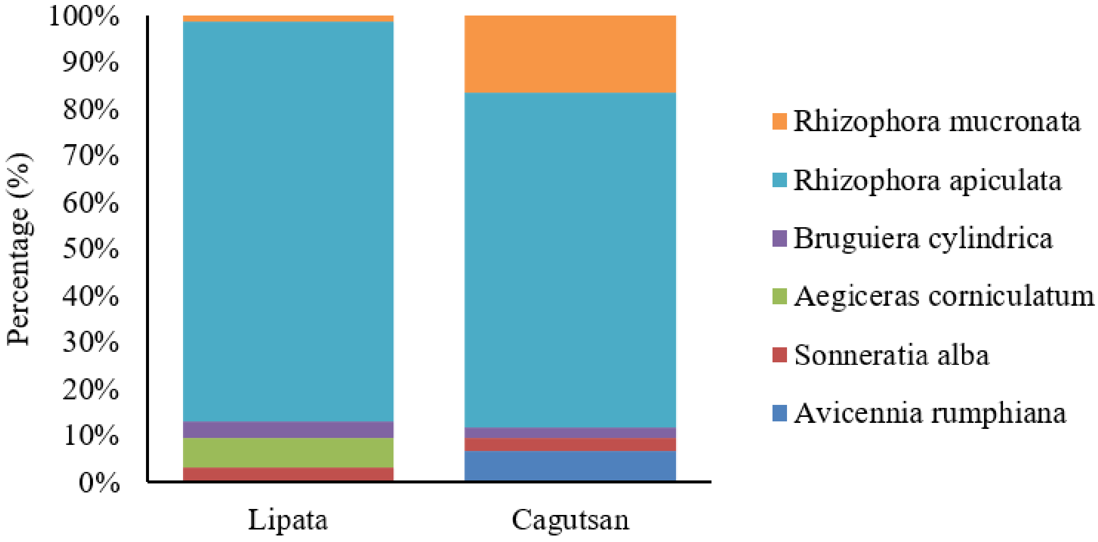

Figure 2. Percentage distribution of species existing in the natural and reforested sites (based on the study of Amparado et al. [11]).

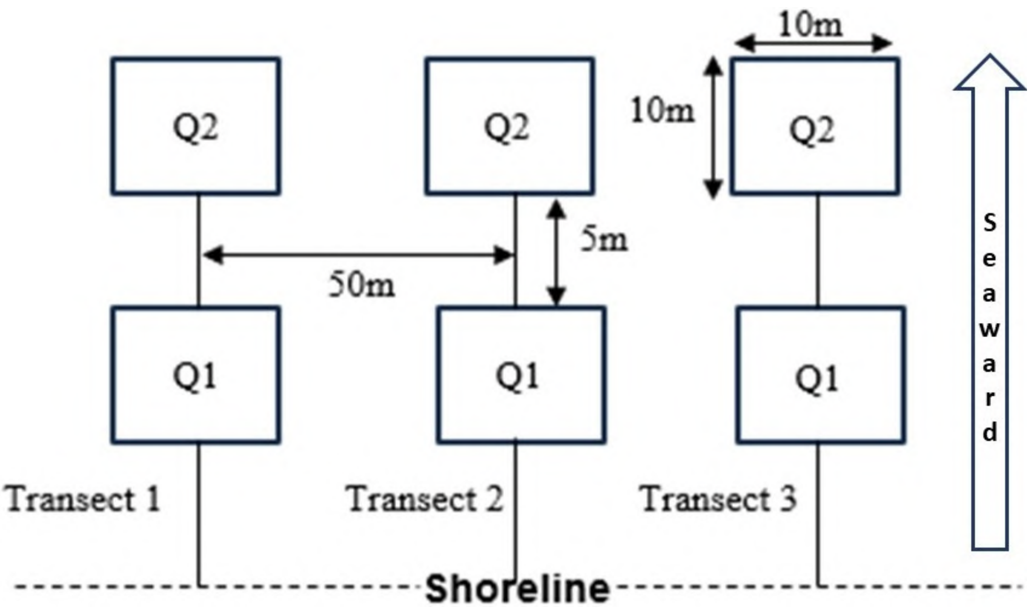

Figure 3. Strip split plot experimental layout used in both mangrove sites in Brgy. Cagutsan and Hinatuan Island, respectively.

2.4. Soil bulk density determination

Soil samples were gathered separately for assessing soil bulk density. The top 100 cm of soil was collected, divided into specific depths of 0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm, respectively. Subsamples were taken at the midpoints of each depth, with depths ranging from 5-10 cm for 0-15 cm depth, 20-25 cm for 15-30 cm depth, 37.5-42.5 cm for 30-50 cm depth, and 77.5-82.5 cm for 50-100 cm depth, to determine bulk density.

The samples underwent oven-drying, the dry mass was then measured to facilitate the calculation of bulk density, employing the adapted formula [12].

Soil Bulk Density was calculated using the equation below:

Bulk Density (g/cm^3) =(oven-dried weight of soil (g))/(volume of soil corer (cm^3))
where volume of the soil $= \pi[r^2h]$.

3. Results and discussion

3.1. Mangrove diameter and height distribution

Based on the diameter at breast height (DBH), both the natural and rehabilitated sites show similar average DBH of 6 cm. in the Lipata site the Bruguiera cylindrica has the biggest (DBH) 23 cm, while the Avicennia rumphiana is the largest in the Cagutsan with a DBH of 54.11 cm. The average height of the Lipata site is 3.4 m while in the Cagutsan site is 3.8 m.

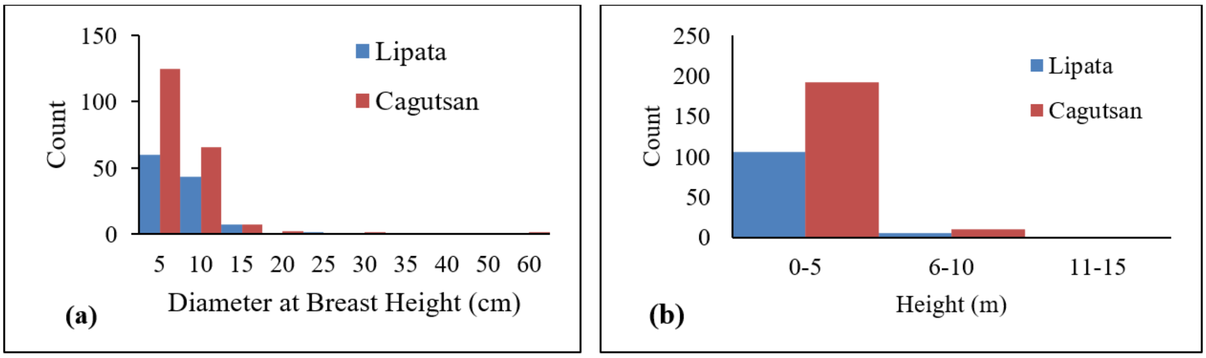

Figure 4. Histogram of (a) diameter at breast height (DBH) and (b) height of tree species in the natural and rehabilitated sites.

In Cagutsan site the Avicennia rumphiana has the largest DBH. Despite not being the most dominant in the area it was able to grow the largest. Cagutsan also has the largest DBH and the highest height compared to the mangroves in Lipata site. The mean DBH of a mangrove stand at Panabo Mangrove Park is 7.67 cm [13] in Zamboanga the mangrove stand has a DBH that range from 5-10 cm [14]. This similarity in mean DBH may indicate a consistent and stable habitat that facilitates similar growth rates among the mangrove species present [14].

Sonneratia alba's emergence as the species with the highest DBH across both sites underscores its adaptability and resilience in different ecological contexts [15]. This species' capacity to attain significant diameters reflects its ability to thrive under varying conditions, making it a vital indicator of the overall health and growth potential of the mangrove ecosystems [16] in Lipata and Cagutsan.

The height further contribute to the differences of these sites. In Lipata, where mangroves predominantly range between 2-4 meters in height, the environment may impose constraints that limit vertical growth. In contrast, the Cagutsan site exhibited a more excellent height distribution, primarily within the 4-6 m range. This discrepancy suggests that environmental factors in Cagutsan, such as nutrient availability or hydrological conditions, may support taller mangrove growth.

The Lipata site is a rehabilitated area hence the DBH of the species found are uniformly similar, compared with Cagutsan site were mangroves are naturally occurring.

3.2. Soil Carbon stock

As the soil got deeper, there was an increasing soil C content. In the rehabilitated site of Lipata the soil C content was 18.76, 24.68, 32.44, and 94.65 MgC/Ha. Post hoc comparison using Tukey HSD test indicates that the soil C content of the rehabilitated site at depth 50-100 cm (M = 94.65; SD = 10.04) is significantly higher compared to the 30-50 cm (M = 32.44; SD = 5.013), 15-30 cm (M = 24.68; SD = 0.73, and 0-15 cm (M = 18.76; SD = 2.59).

In the natural mangrove stand of Cagutsan, the soil C content is also lowest at 0-15 cm with 30.49 MgC/Ha and increased to 32.34MgC/Ha at 15-30 cm, 41.80MgC/Ha at 30-50 cm and up to 109.72 MgC/Ha at 50-100 cm depth. Significant difference was also observed in the soil C content between soil depth $F\ (3,12) = 233.32$, $p < .0000$. Similarly based on the Post hoc Tukeys HSD test 50-100 cm is significantly higher compared to the shallower soil depth. No significant difference was found in the average soil C content across the transect traversing from the landward to the seaward zones within each of the natural mangrove's sites of Cagutsan and the rehabilitated site of Lipata.

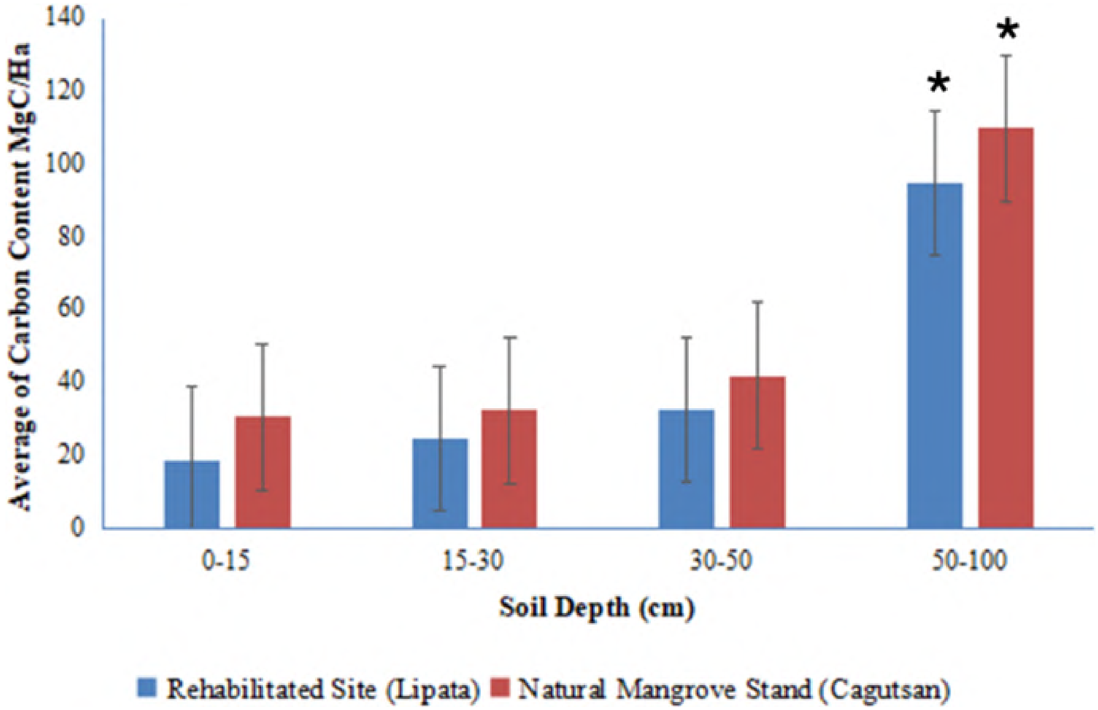

Figure 5. Average soil carbon content at varying soil depths from 0 to 100 cm at the natural mangrove stand and rehabilitated mangrove site. Asterisk above the bars indicate significant difference compared to the other depth at $p < 0.01$ based on Tukey post hoc test.

The higher soil carbon stock in the Cagutsan site suggests that this mangrove ecosystem is particularly effective in sequestering and storing carbon compared to the Lipata site. The average carbon stock is like the carbon stock of the other places in the Philippines where in Honda Bay the average carbon stock is 71.7 MgC/Ha [17].

Understanding the variations in soil carbon stock has broader implications, particularly in the context of climate change mitigation. Recognizing mangrove ecosystems as significant carbon sinks, the differences observed between Cagutsan and Lipata underscore the need for tailored conservation and management strategies. Conservation and protection efforts in areas with higher carbon sequestration potential, like Cagutsan, can contribute to regional and global climate change mitigation goals.

The observed consistent upward trend in soil carbon content with increasing soil depth in both the Cagutsan and Lipata mangrove sites provides valuable insights into the vertical distribution of carbon within these ecosystems. This trend, as illustrated in Figure 5, indicates that deeper soil layers harbor progressively higher concentrations of carbon, highlighting the significance of considering different soil depths when assessing carbon dynamics in mangrove environments [18, 19].

In the Cagutsan site, the specific values of soil carbon content further emphasize the substantial increase with depth. The recorded values of 30.49, 32.34, 41.8, and 109.7 Mg C ha^{-1} for depths ranging from 0-15, 15-30, 30-50, and 50-100 cm, respectively, showcase a notable carbon accumulation as the soil extends deeper into the substrate. This finding aligns with the recognized capacity of mangrove ecosystems to sequester and store substantial amounts of carbon in their soils, particularly in deeper layers.

The depth-dependent variations in soil carbon content reflect the complex interplay of factors influencing carbon dynamics, including root contributions, microbial activities, and organic matter decomposition. Deeper soil layers often serve as repositories for long-term carbon storage, playing a crucial role in the overall carbon budget of mangrove ecosystems. Understanding the vertical distribution of soil carbon has implications for accurately estimating carbon stocks and assessing the potential impacts of environmental changes on carbon sequestration. The observed trend underscores the importance of preserving deeper soil horizons within mangrove habitats to maintain robust carbon storage capacities [20].

The 50-100 cm depth emerges as a critical zone influencing the overall carbon stocks within these mangrove ecosystems. Deeper soil layers often serve as reservoirs for organic matter accumulation, and the observed disparities in this specific depth range suggest that the factors influencing carbon sequestration may differ significantly between shallower and deeper horizons.

The depth-specific disparities in soil carbon content affect our understanding of carbon sequestration processes in mangrove ecosystems.

Understanding the relationship between DBH, height and below-ground carbon stock is important for accurately estimating the carbon sequestration potential of forests. Larger trees, due to their higher biomass and more extensive root systems, can play a significant role in storing carbon [21].

4. Conclusion

Comparing the mean DBH, height and carbon stock of mangroves provides an insight of the mangrove stand carbon sequestration potential. The mangrove rehabilitated site of Lipata has similar mean DBH, height and below ground carbon stock. Hence the rehabilitation efforts of the Lipata site in Hinatuan Island must be continued and should also be implemented in the nearby damaged mangrove ecosystems.

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Accumulation of heavy metals by different representatives of biota in the operation zone of the Prydniprovska thermal power plant

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Accumulation of heavy metals by different representatives of biota in the operation zone of the Prydniprovska thermal power plant

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Abstract. Among the consequences of technoecogenic stress caused by the activity of industrial and energy complexes, dust and gas emissions, containing toxic to representatives of biota substances, including heavy metals, have a particularly negative impact on ecosystems. Different types of organisms have different mechanisms to absorb and accumulate heavy metals, that can be used for ecotoxicological studies. The peculiarities of the accumulation of heavy metals in various components of the ecosystem such as soil – plant – animal in the area of operation of the thermal power plant (TPP) of the Dnipro region were investigated. Test samples of soil, sod-forming grasses, and soil-litter invertebrates were collected from artificial plantations of Robinia pseudoacacia L., located in the immediate vicinity of the Prydniprovska TPP in the city of Dnipro, and control samples – at a distance of 30–40 km from the TPP. Determination of the content of heavy metals, which are priority pollutants for the Dnipro region, was carried out by the method of atomic adsorption spectrophotometry according to the standard method. The invertebrates accumulate Fe and Mn in the largest amount at all test sites. From all functional groups, only representatives of saprophages perform the functions of heavy metal accumulators (Fe, Cu, Cd, Mn), contributing to the intensification of the biological cycle (Ni) and the purification of trophic chains (Zn, Pb). The features of the accumulation of heavy metals by the main sod-forming cereals depending on the contamination level in the soil under the influence of the Prydniprovska TPP have been established. The concentration of heavy metals in both the above-ground mass and the underground part of the plants was determined in the experimental and control plots. The different intensity in the elements accumulation by the vegetative organs of the experimental plant species was revealed. The obtained results can be used in bioindication to assess environmental pollution.

1. Introduction

Various types of natural minerals, including hard coal, are intensively used by the industry of Ukraine and its energy complexes. The operation of industrial and energy complexes leads to technogenic stress on natural and artificial ecosystems. Ecosystems are mostly affected negatively by pollution of the air basin with dust and gas emissions [1–3]. The toxic substances found in these emanations include heavy metals. Together with dust emissions, they enter the soil as the habitat of most representatives of the biota [4, 5].

Degradation of natural vegetation begins even during the construction of industrial enterprises. In the future, the state of the environment will worsen. The effect of constant, even one-time, dust emissions can lead to catastrophic consequences. Therefore, those forms of anthropogenic impact on the environment that positively regulate the balance of functioning components, play a significant role [5–7].

Excessive entry of heavy metal ions into cells leads to irreversible changes and disturbances of the vital functions of the plant organism at the morphological, physiological and biochemical level. When accumulating in plant tissues, heavy metal ions displace metals in the active centre of enzymes and thus encourage cells to increase metabolism. There is a gradual dieback of the leaf plate. This process is primarily manifested by necrotic lesions and later leads to its aging and death. In particular, lead in plant cells causes inhibition of ATP production, lipid peroxidation and DNA damage [8, 9]. Each type of plant shows individual characteristics regarding the accumulation of heavy elements. These properties of plants can be used in the biological remediation of areas polluted, particularly by heavy metals [10–14].

Heavy metals are accumulated by plants in the roots and leaves. The processes of their adsorption by roots and leaves are different: in the first case, the ions pass through the cell wall, and in the second – through stomata or through the cuticle of the epidermis. Together with the transport metabolites, a part of the accumulated toxic substances is exported. The cuticle, the thickness and chemical composition of which on the outer surface of the epidermal cells varies greatly depending on the type of plant, its age, systematic position, living conditions, etc., consists of cutin impregnated with wax and is a complex mixture of long-chain alkanes, alcohols, ketones, complex ethers and carboxylic acids, which is a universal adaptation of plants to environmental conditions [15].

Depending on the specific characteristics of the accumulation of heavy metals, plants can be accumulators absorbing metals even with a low amount of them in the environment; indicators, in which the metal content is directly proportional to its content in the environment, and exceptions, in which a low concentration of metals in vegetative organs is maintained regardless of their concentration in the environment. Different indicators of heavy metals accumulation [16] are the result of their selective absorption by living organisms, the quantitative characteristic of which is the coefficient of biological absorption (the ratio of the content of the element in a living object to the content in the substrate). The study of biological absorption coefficients (BAC) allows to distinguish groups of ground cover plants according to the degree of heavy metal absorption. Organisms with BAC>10 refer to energy accumulators. The plant with a BAC 10–1 absorb elements strongly. The plants with BAC <1 are deconcentrators [17, 18].

Local dust emissions lead to the direct introduction of heavy metals into the soil. Soil, plants, and animals are the most important links to the technoecogenic migration of chemical elements. In the soil, the prevalence of trace elements affects the supply of these elements to living organisms. Signs of soil poisoning appear later than air and water [19–21].

The peculiarity of the influence of heavy metals is that when entering the ecosystem, they do not decompose for a long time and accumulate in the tissues of living organisms, in particular in the soil, litter and invertebrates. Invertebrates are litter and soil inhabitants and in terrestrial ecosystems they are represented by such functional groups as phytophages, zoophages, and saprophages. Like plants, they are able to exist in conditions of anthropogenic pressure: during the feeding process, they accumulate various chemical elements, including heavy metals in the zone of technogenic stress [13, 22].

In the body of invertebrates, the concentration of heavy metals depends on the nature of their nutrition and the content of toxicants in their habitat. According to the nature of chemical elements accumulation, terrestrial animals are divided into three geochemical groups:

1) accumulators – the content of trace elements in the animal tissues is higher than in the food object (accumulation coefficient does not exceed 1);
2) scatterers – the trace element content is the same as the power source (accumulation coefficient is about 1). They contribute to the intensification of the biogenic cycle;
3) cleaners – the content of trace elements in the animal is much lower than in the food object (accumulation coefficient is less than 1), contributing to the cleaning of the trophic chain.

The nature of heavy metals migration along the trophic food chains of the animals, namely the invertebrate inhabitants of the soil and litter, and the determination of threshold loads both on individual taxa of animals and for the ecosystem as a whole arouses interest.

The purpose of the study was to establish the features of heavy metals accumulation in various components of the ecosystem: soil-plant-animal in the area of Prydniprovska regional TPP operation.

2. Methodology

Materials of plant and animal origin and soil samples were used for the research. Representatives of soil and litter invertebrates, samples of soil and sod-forming cereals to determine the content of heavy metals were selected in artificial plantations of Robinia pseudoacacia L., located in immediate proximity to the Prydniprovska TPP in Dnipro (figure 1).

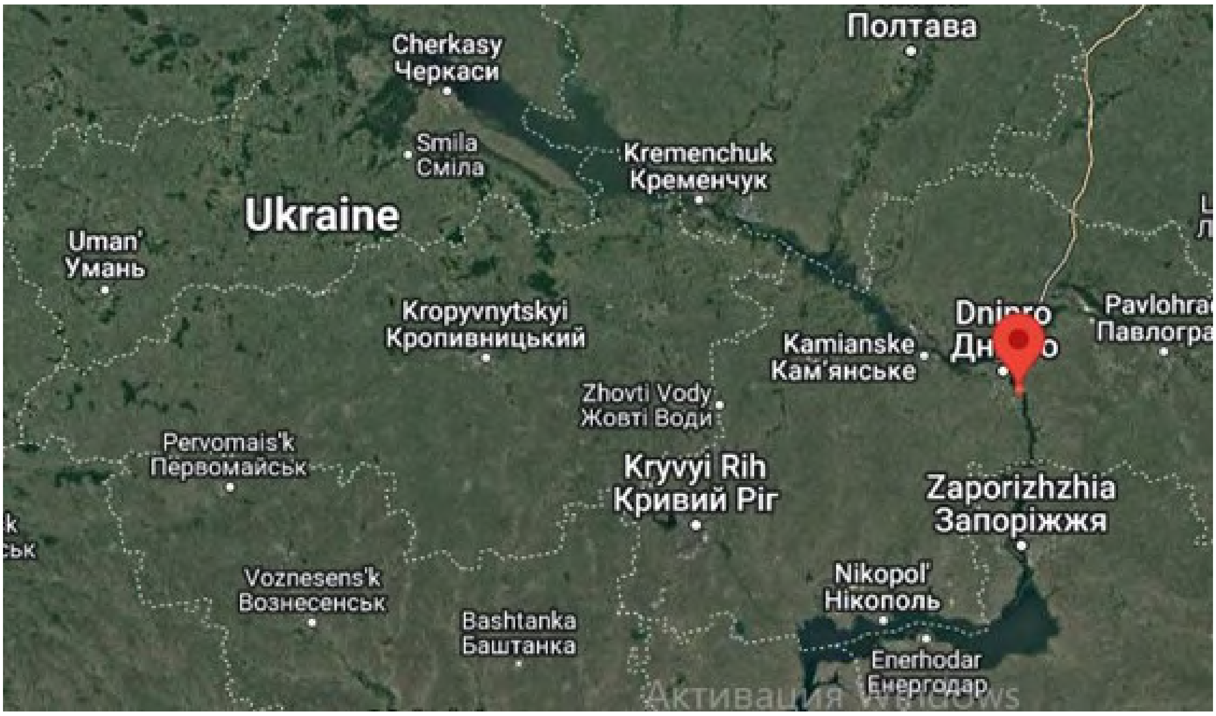

Figure 1. Location of Prydniprovska TPP in Dnipro.

Areas with artificial woody plantations at a distance of 30–40 km from the TPP were used as controls. At the same time, the direction of the winds was taken into account. Soil samples were taken at a depth of 20 cm.

The roots and leaves of the main regional sod-forming grasses – Poa angustifolia L., 1753 and Elytrigia repens (L.) Nevski, 1933 – was used for ecophytoxicological studies.

For the determination of the taxonomic composition of soil and litter invertebrates and the selection of material for animal zooecotoxicological studies Barber's traps were used. Taking into account the functional affiliation of insects, the content of heavy metals was determined only in Histeridae, Carabidae, and Cerambycidae.

The determination of heavy metals content in the invertebrate animals tissues, plant material and soil was carried out by the method of atomic adsorption spectrophotometry according to the standard method using an AAS 30 spectrophotometer [5, 13, 22, 23].

The coefficients of biological absorption (BAC) of heavy metals by the roots and leaves of the experimental plants were calculated.

To detect the presence of a root barrier in the experimental plants, the root barrier coefficient (RBC) was calculated as the ratio of the element content in the roots to its content in the above-ground organs. A RBC value greater than one indicates the presence of a root barrier in the elements absorption by the plants.

The bioaccumulation index (BAI) as the ratio of the heavy metals content in the invertebrates representatives to the heavy metals content in the objects of their nutrition or habitat was calculated. For representatives of saprophages, the ratio of trace elements in the soil (habitat), and for zoophages, the trace elements content in phytophages representatives (Cerambycidae) as potential objects of their nutrition was calculated.

The Statistica software package for statistical processing of the received data was used. The statistical significance was considered at $p<0.05$. [24, 25].

3. Results and discussion

As a result of the research, it was established that the iron ions content in the soil of the research area is fully consistent with the metal content in the lithosphere, soil cover and basic geological rocks [23]. The manganese concentration exceeded the reference indicators but probably did not differ from the indexes of industrially polluted areas. The nickel content slightly exceeded the control metal content. The levels of zinc, copper, cadmium, and lead exceeded the reference values (figure 2, 3).

In the course of the experiment, different intensity of the elements accumulation by vegetative organs of different types of plants was revealed. Thus, in the control area, a significant content of manganese and copper in the roots of Poa angustifolia L., and manganese, zinc, and copper in Elytrigia repens (L.) was noted. In the experimental plants, an accumulation of manganese was observed in the subterranean part (Poa angustifolia L.), copper and zinc (Elytrigia repens (L.)).

In the ground part of Poa angustifolia L. growing in the control and experimental plots, a further increase in the content of copper and cadmium was noted in comparison with their level in the soil and roots. For Elytrigia repens (L.) Nevski, a lower concentration of almost all determined heavy metals was characteristic compared to ones in soils and Poa angustifolia L.. the exception was nickel.

When comparing the absorption intensity of each of the heavy metals of Poa angustifolia L. and Elytrigia repens (L.) Nevski, it was established that in the control plots, the concentration of manganese and iron in the roots of Poa angustifolia L. was lower than the similar indicators of Elytrigia repens (L.) Nevski, by 1.1 times, zinc and nickel by 1.2 times. In the aerial part of the experimental plants, the difference in heavy metal concentrations was 1.5 times for manganese and cadmium.

For plants of the experimental variant, the concentration of manganese and iron in the roots of Elytrigia repens (L.) Nevski exceeded the content in the underground part of Poa angustifolia L. by 2 times. In the experimental variant, a significant excess of copper content in the aerial part of Poa angustifolia L. compared to Elytrigia repens (L.) Nevski was noted. Such a difference in the intensity of the heavy metals absorption at the plants indicates the species specificity of their accumulation.

A different level of heavy metals accumulation was also noted for plants affected by the emissions of thermal power plants growing in forest areas of Europe [26].

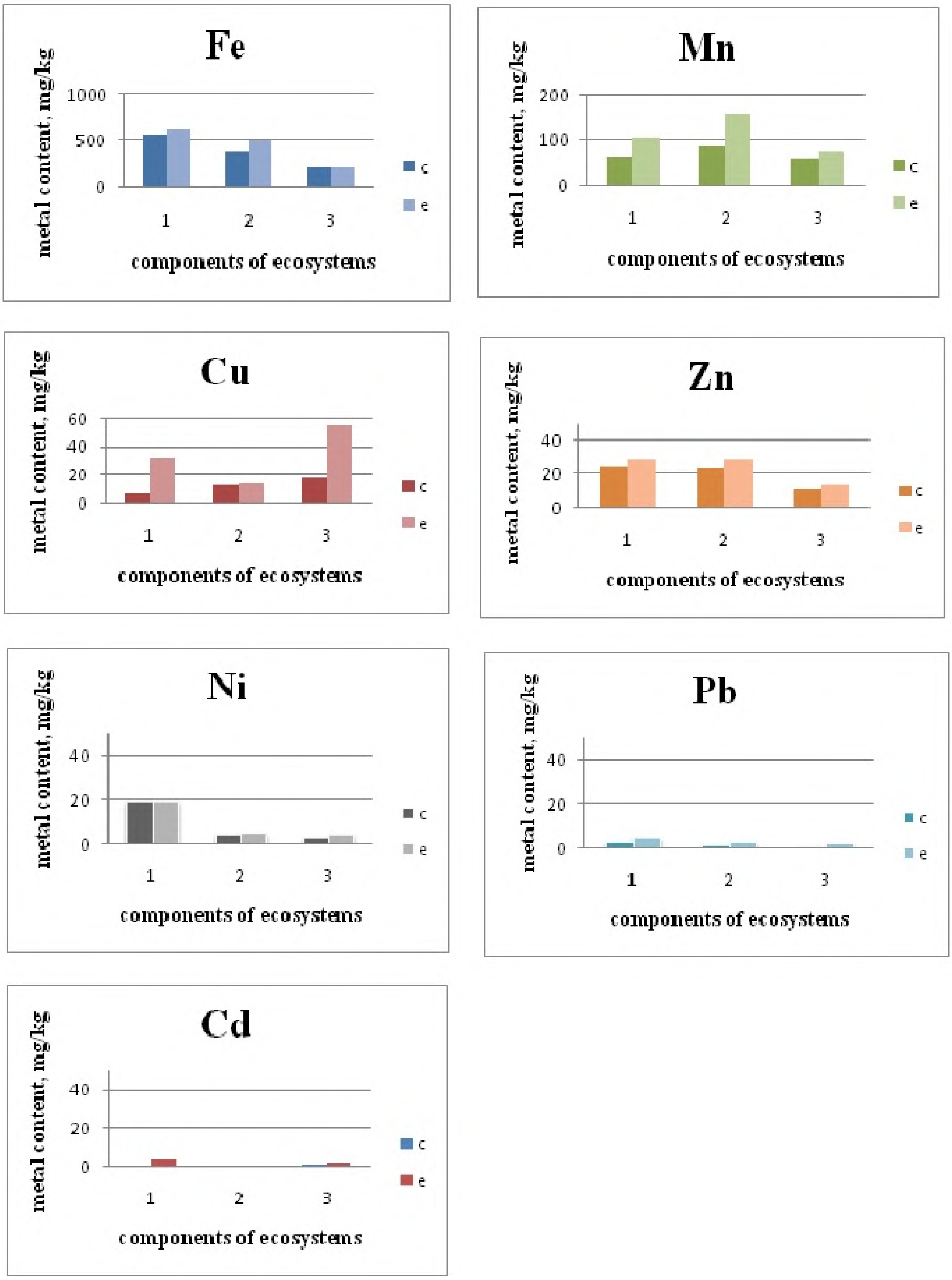

Figure 2. The content of heavy metals in various components of ecosystems under conditions of environmental pollution (Poa angustifolia L.), mg/kg: 1 – soil, 2 – underground part, 3 – above-ground part; k – control, d – experiment.

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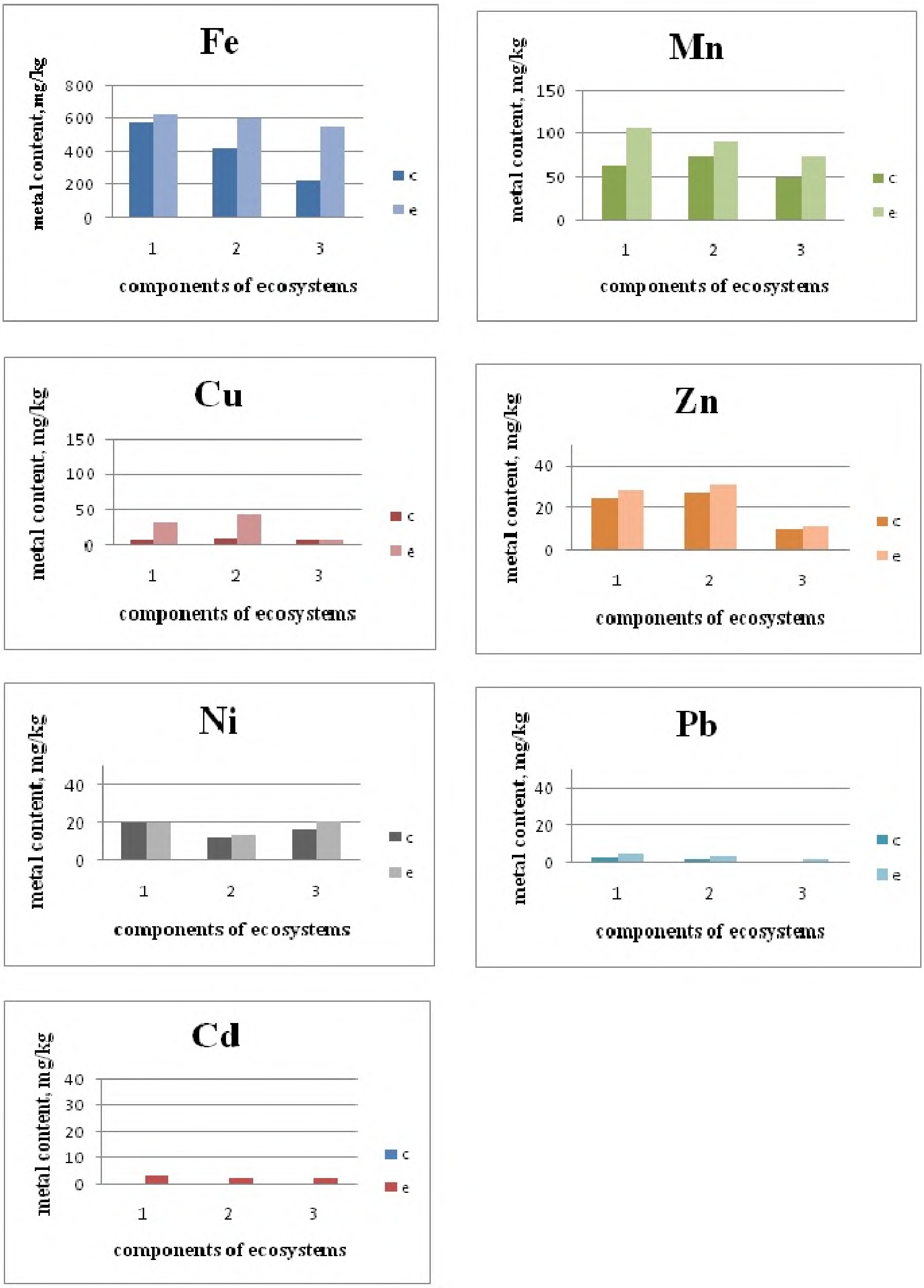

Figure 3. The content of heavy metals in various components of ecosystems under conditions of environmental pollution (Elytrigia repens L..), mg/kg: 1 – soil, 2 – underground part, 3 – above-ground part; k – control, d – experiment.

The conducted studies showed that, as a rule, the highest level of elements accumulated in the roots, which confirms the existence of a physiological protective barrier allowing heavy metals to penetrate into the plant aerial part selectively.

Along with plants, soil invertebrates are an integral part of the biota in artificial plantations of Robinia pseudoacacia L. in the area of Prydniprovska TPS operation. It was found that in artificial plantings of Robinia pseudoacacia L., the population of soil and litter invertebrates is represented by crustaceans, molluscs, arachnids, and insects. They are characterized by high numbers, species richness and diversity of functional groups. In all white acacia plantations, the greatest taxonomic diversity is among representatives of the class Jusecta – Scarabaeidae, Staphylinidae, Carabidae, Silphidae, Tenebrionidae, Histeridae, Cerambycidae. In animals selected in the area of influence of the Prydniprovska TPP and in the control areas Zn content for representatives of Isopoda, Cerambycidae, Carabidae, is almost the same and has the level as 18.1–19.6 mg/kg (figure 4). In the TPP area, soil and litter invertebrates accumulate iron (at the level of 2640.0 – 1450.0 mg/kg) and manganese (at the level of 1480.3 – 960.5 mg/kg) to a greater extent. In the control area, the research objects accumulated 1.2–1.3 times less iron, and 1.3–1.7 times less manganese compared to the contaminated area. Animals accumulate Zn and Ni in the smallest amount at all test sites. Among the highly toxic trace elements present in invertebrates, lead accumulates to a greater extent than cadmium. In the TPP area in representatives of crustaceans, its content is almost two times higher than in animals from control areas. For representatives of arachnids, the Pb content indicators exceed the control by 1.5 times. This shows that heavy metals are present in the dust emissions of Prydniprovska TPP and soil and litter invertebrates accumulate them in the process of life. It can be assumed that the differences in the content of some microelements (Zn and Ni) in the animals studied in TPP operation area compared to the control, are related to the presence of trace elements in the fuel on which the TPP works.

Accumulation of heavy metals by representatives of soil and litter invertebrates occurs in the process of their nutrition. Each animal performs its ecological and geochemical functions, taking part in the cycle of trace elements. Vertebrates feed on invertebrates. In this way, toxic microelements accumulated by invertebrates enter trophic food chains. In the process of research, the features of the heavy metals accumulation by invertebrates, which belong to such functional groups as zoophages and saprophages, were determined. The index of biological accumulation by representatives of individual taxa belonging to certain functional groups was calculated (figure 5).

The object of food of saprophages is leafy plant debris from which litter is formed. The litter is considered as the upper soil horizon. The process of feeding saprophages is closely related to plant material. By crushing dead plant debris, they promote the migration of heavy metals from it into deeper soil horizons. Woodlice (Isopoda sp.) are typical representatives of saprophages. At all test sites, they intensively accumulate Fe, Mn, Cu, Cd. (BAI more than 1). At the same time, they contribute to the purification of trophic food chains from Zn and Pb (BAI less than 1) and intensify the biological cycle of Ni (BAI = 1). Arachnids are typical zoophages. They feed on other invertebrates. In all studied artificial white acacia plantations, both control and in the TPP area, arachnids actively accumulate Fe, Cu, Zn, Ni, Pb, Cd (BAI greater than 1) and contribute to cleaning the trophic chain from Mn.Histeridae. Representatives of zoophages among insects intensively accumulate heavy metals in all investigated test areas (BAI more than 1). Carabidae sp., like Histeridae sp., accumulate Fe, Mn, Cu, Ni, Pb, Cd at all test sites, they contribute to the intensification of Zn circulation (BAI=1). Carabidae sp. is a fairly plastic group of insects with a high number and species richness of representatives. The bioaccumulation index for Fe, Mn, Ni, Pb practically approaches 1 in this objects. Thus, under certain conditions, they can contribute to the intensification of the circulation of these trace elements.

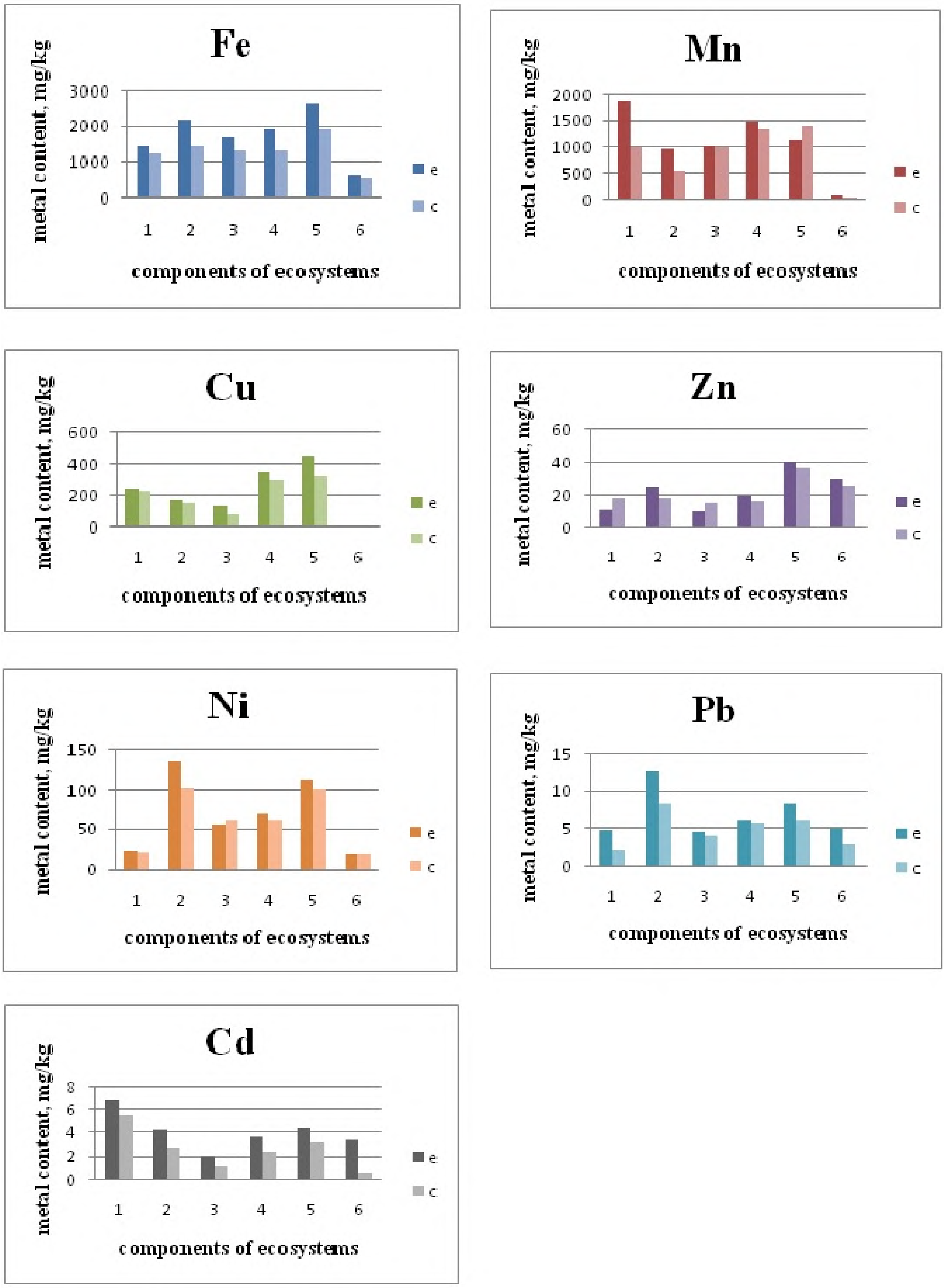

Figure 4. Average statistics of heavy metals accumulation by representatives of soil-litter invertebrates in artificial Robinia pseudoacacia L. stands (white acacia) in the area of Prydniprovska TPP operation; 1 – Isopoda, 2 – Aranei, 3 – Cerambycidae, 4 – Carabidae, 5 – Histeridae, 6 – Soil, d – experiment, k – control.

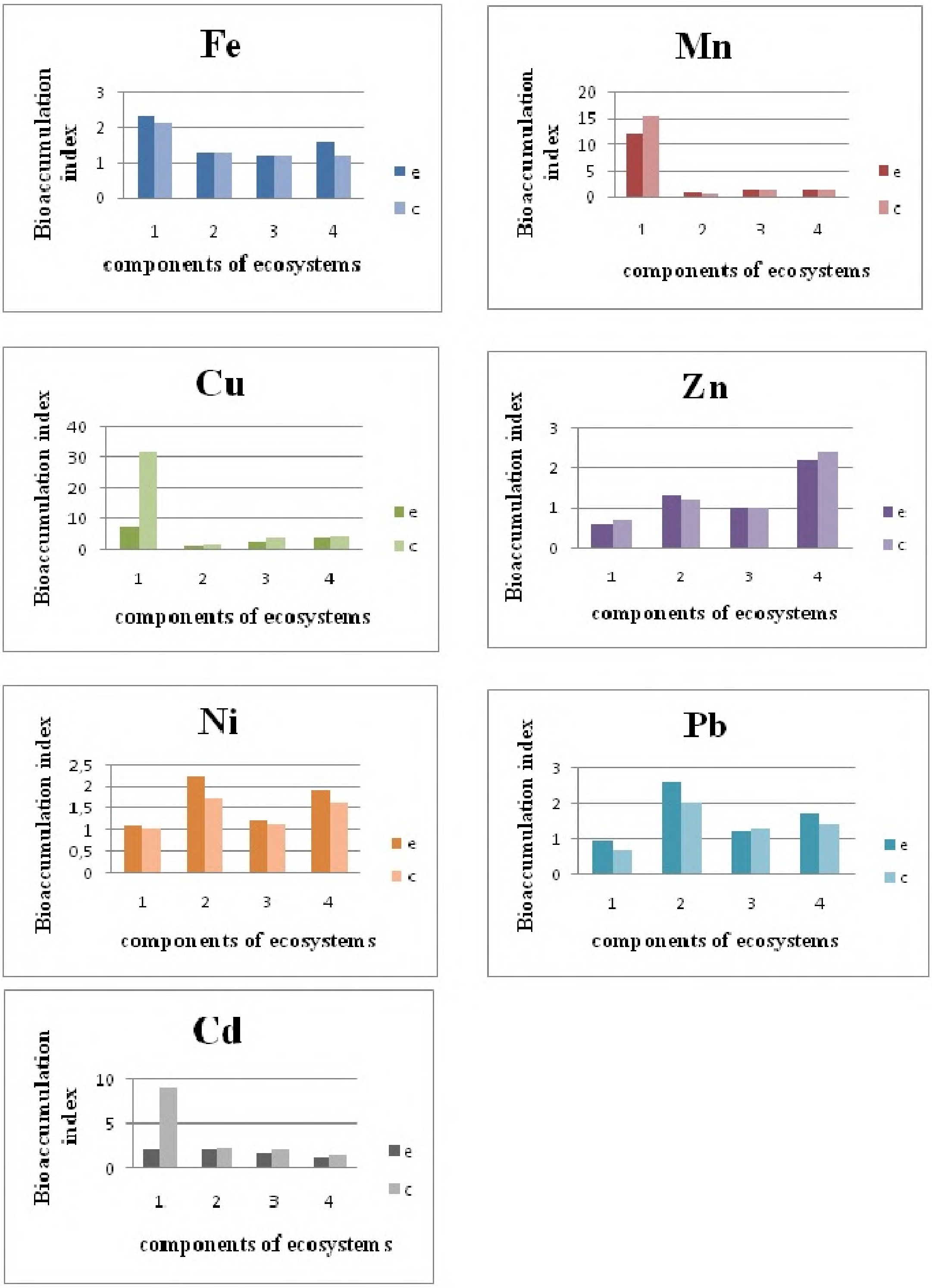

Figure 5. Index of biological accumulation of representatives of soil and litter invertebrates in artificial Robinia pseudoacacia L. (white acacia) plantations in the area of Prydniprovska TPP operation and in control areas; 1 – Isopoda, 2 – Aranei, 3 – Carabidae, 4 – Histeridae, d – experiment, k – control.

4. Conclusions

Based on the conducted research, it was established peculiarities in the accumulation of heavy metals by the main sod-forming cereals, depending on the level of soil pollution in the plantings of Robinia pseudoacacia L. in the area of the Prydniprovska TPP operation. It was found that in the soil of the experimental site, the content of zinc, copper, cadmium, and lead exceeded the reference indicators, and the excess was significant for manganese and nickel. The peculiarities of the heavy metals accumulation in the above-ground and underground parts of the main sod-forming grasses growing on the TPP territory were revealed.

Soil-litter invertebrates living in Robinia pseudoacacia L. plantations in the area of Prydniprovska TPP operation and control sites accumulate heavy metals Fe, Cu, Zn, Ni, Mn, including highly toxic Pb and Cd. In the control and experimental areas indicators of Zn accumulation by invertebrates do not differ significantly. At all test sites, invertebrates accumulate Fe and Mn in the largest amount. Of all the functional groups, only representatives of saprophages perform the functions of the heavy metals accumulators (Fe, Cu, Cd, Mn), contribute to the intensification of the biological cycle (Ni) and the purification of trophic chains (Zn, Pb). The obtained results can be used for conducting monitoring ecotoxicological studies. Certain taxa of soil and litter invertebrates (Carabidae sp., Cerambycidae sp.) can be used as bioindicators of the state of the environment.

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ML-ERV: A machine learning-based CO_2 emissions model designed for rental vehicles

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Abstract. On-road carbon dioxide (CO_2) emissions from rental vehicles are very much affected by vehicle category, types of vehicle transmission, fuel type and traveled distance. In this paper, four machine learning models (decision trees, random forest, AdaBoost and XGBoost) were used to predict CO_2 emissions from rental vehicles. The models were trained and tested on Carbookr's bookings dataset. The results show that the traveled distance, the included mileage, the ACRISS code, the rental duration, the driver's home country, the country where the driver works and the country where he pickups up the vehicle as well as the country where he returns the vehicle had clear impacts on the transient CO_2 emission rates. There was a positive correlation between these features and CO_2 emission rates. The findings also indicate that XGBoost achieves the best accuracy performance when compared to other machine learning algorithms in terms of the Root Mean Squared Error (RMSE), the Mean Absolute Error (MAE), the Mean Absolute Percentage Error (MAPE) and the Coefficient of Determination (R^2). The results show that the machine learning-based CO_2 emission model ML-ERV trained using XGBoost algorithm outperforms the state-of-the-art CO_2 emissions calculators.

1. Introduction

Carbon dioxide (CO_2) emissions from the transportation sector are one of the largest contributors to greenhouse gas emissions [1]. These emissions are a result of fossil fuel combustion in various types of transportation such as road transportation, maritime transportation, aviation, public transit, and rail transportation. The percentage of CO_2 emissions per transportation type can change over time due to many factors including advancements and shifts in transportation habits [2]. However, according to [3–5], nowadays, road transportation, which includes rental vehicles and individually owned vehicles, releases a significant amount of CO_2. It accounts for a substantial portion of total greenhouse gas emissions. Rental vehicles, which might be cars, trucks, vans, and buses, contribute to CO_2 emissions in the same way as individually owned vehicles. In what follows, we will focus on CO_2 emissions from rental vehicles.

France has various environmental regulations and policies in place related to CO_2 emissions from rental vehicles. These regulations aim to reduce greenhouse gas emissions which do not only have environmental benefits but also wide-ranging positive impacts on both public health and economic well-being. Indeed, decreasing CO_2 emissions from rental vehicles will mitigate climate change, protect ecosystems, ensure cleaner air, improve physical and mental health, reduce healthcare costs associated with treating pollution-related illnesses, lower fuel consumption which leads to cost savings for both consumers and businesses, and encourage companies to become more innovative and competitive.

Environmentally friendly vehicles, including electric vehicles (EVs) and hybrids, are nowadays being promoted by rental vehicle companies as a vital solution to effectively tackle climate change [6]. However, transitioning to environmentally friendly vehicles for rental vehicle companies can be challenging for various reasons. The following are some of the common challenges associated with making this switch: limited charging stations or repair facilities, higher purchase price compared to traditional gasoline-powered vehicles, limited driving ranges which can be an issue for individuals who travel long distances without regular charging options, lack of variety compared to traditional vehicles, and charging a vehicle takes much more time than filling up a gasoline tank.

Calculating and reporting CO_2 emissions from rental vehicles can contribute significantly to reducing CO_2 emissions. Here are some common ways that help mitigate CO_2 emissions given CO_2 emissions reports: it serves as a reference point for understanding the current environmental impact of rental vehicles, which helps identify sources with high CO_2 emissions and thus come up with solutions to help reduce these emissions, it brings more awareness to eco-driving practices, customers make a more sustainable choice when selecting a rental vehicle (opt for lower-emission vehicles), it enhances the company's brand image by promoting sustainability, it assists companies to better comply with regulations and avoid penalties related to CO_2 emissions, and it helps companies manage their fleets by offering vehicles with varying emissions based on customer preferences and local regulations.

Valuable as it is, developing a machine learning model to predict CO_2 emissions from rental vehicles is complicated as it faces numerous challenges, which includes lack of rental vehicle bookings datasets, often unavailable data about the traveled distance, missing information about the customer's driving style (aggressive braking, gentle braking, etc.), missing information about the places the driver will visit (cities, rural areas, highway, mountains, etc.), lack of information about the number of passengers and baggage, unavailable information about the weather and traffic conditions, etc.

In this paper, we introduce an unprecedented machine learning-based CO_2 emissions model designed for rental vehicles (ML-ERV). ML-ERV was built using a dataset from Carbookr's bookings. Carbookr (`https://www.carbookr.com/`) is a car booking platform for business travels. The key idea of ML-ERV is to predict CO_2 emissions from a vehicle prior to renting it. ML-ERV is an innovative and environmentally responsible solution for both rental vehicle companies and consumers. We make the following contributions:

- Introduce a new machine learning-based CO_2 emission model, ML-ERV, designed for rental vehicles and trained using XGBoost algorithm.
- Provide a CO_2 emission calculating solution that takes into consideration information closely related to the rental vehicle domain.
- Develop a CO_2 emission model with a high accuracy and a very low percent error.
- Make better predictions than existing CO_2 emissions calculators.

The rest of this paper is organized as follows. Section 2 reviews the state-of-the-art CO_2 emissions calculators, and then presents their key limitations. Section 3 describes ML-ERV, and compares it against current CO_2 emissions calculators. Section 5 concludes this paper and discusses future research directions.

2. Literature review
Plenty of research work has been conducted on calculating CO_2 emissions from vehicles. However, to our knowledge, none has been designed for tracking and managing CO_2 emissions generated by vehicles in a rental fleet. In the following, we will review the state-of-the-art calculation methods of CO_2 emissions from vehicles. We grouped them into four major categories, each using a different set of information about the vehicle and the travel specifics.

2.1. Calculators using distance

Numerous research works [7] have defined CO_2 emission factors for a specific city; however, these factors cannot be used in other locations because the emission factor depends on the type of the vehicle, the passenger load factor, and the engine size. Furthermore, the number of vehicles on the road during peak hours differs for different study locations. Given all that, Wei and Pan [8] introduces equation (1) to calculate CO_2 emissions, such that M_i refers to CO_2 emissions, D_i is the distance, and E_i is the CO_2 emission factor.

$$M_i = D_i \cdot E_i \tag{1}$$

2.2. Calculators based on vehicle type

Aksoy et al. [9] introduces a CO_2 emission calculating method that uses vehicle type. This method uses the vehicle weight, the vehicle technical data as well as the distance traveled. Researchers found that CO_2 emissions are directly correlated with vehicle type and distance traveled, where higher fuel consumption leads to higher CO_2 emissions. The formula (2) presents their contribution where C refers to CO_2 emissions (kg), FC is the vehicle fuel consumption (L/100 km) and f is the fuel-based emission factor (kg/L).

$$C = FC \cdot f \tag{2}$$

2.3. Calculators based on fuel consumption

According to Zahoor et al. [10], CO_2 emissions from vehicles are calculated based on the combustion of different types of fossil fuels (petrol, gas, diesel, kerosene-oil, etc.). Zahoor et al. [10] indicates how to calculate these emissions, such that $Fuel_i$ is the mass of fuel type i, HC_i is the heat capacity of fuel type i, C_i is the carbon content of fuel type i, FO_i is the oxidized fraction of fuel type i, CO_2(m,w) is the molecular weight of CO_2, $C(m, w)$ is the molecular weight of carbon. The equation is defined as follows:

$$Emission = \sum_{k=0}^{n} \mathrm{Fuel}_i \times \mathrm{HC}_i \times C_i \times \mathrm{FO}_i \left(\frac{\mathrm{CO}_2(m, w)}{\mathrm{C}(m, w)} \right) \tag{3}$$

Weigel, Southworth and Meyer [11] introduces an improved equation (4) of the previous measure. (4) uses the volume of fuel, the measured carbon content of the fuel per unit of energy (or per unit of volume or mass) and the measured heat content (or density) of the fuel used. F refers to the fuel consumption, R is the thermal capacity or density of the fuel and K is the carbon content.

$$E = F \cdot R \cdot K \cdot \left(\frac{11}{3} \right) \tag{4}$$

2.4. Calculator using the average vehicle speed

Gharineiat and Khalfan [12] presents an average vehicle speed-based measure. It calculates CO_2 emissions $f(x)$ as showed in equation (5) presented below, where v_s is the average speed in km/h, f_i is the fuel consumption rate in mL/h, c is a derived regression coefficient, K is the adjustment factor and the constant term cK takes into account inertia and effect of slope on fuel.

$$f(x) = f_i \cdot v_s + c \cdot K \tag{5}$$

Table 1 presents the key features each of the aforementioned CO_2 emissions calculators takes into consideration.

Current vehicle emission models are either overly simple not using enough information, resulting in low estimation accuracy, or they are too complicated requiring excessive inputs,

Table 1. State-of-the-art CO_2 emissions calculators.

CO_2 calculators	Distance	Fuel type	Fuel consumption	Speed	Vehicle type	Manufacturer	Model	Year
Equation (1)	✓	✗	✗	✗	✓	✗	✗	✗
Equation (2)	✓	✗	✓	✗	✓	✗	✗	✗
Equation (3)	✗	✓	✓	✗	✗	✗	✗	✗
Equation (4)	✗	✓	✓	✗	✗	✗	✗	✗
Equation (5)	✗	✗	✓	✓	✓	✗	✗	✗

relying on too much prior knowledge [13–16]. Each calculating method described above has its own pros and cons (table 1), but one thing that all these calculators have in common is that they were not defined to fit rental vehicle needs. Thus, they do not meet the unique requirements and challenges a calculator of CO_2 emissions from rental vehicles should comply with. Below we will present these requirements:

- Predicting CO_2 emissions prior to renting the vehicle.
- Using the distance traveled during the rental duration.
- Profiling drivers.
- Using precise information about the vehicle (category, type, transmission, fuel, etc.).
- Using the driver's place of work, vehicle pickup station, vehicle return station and home address.

In the next section, we will present thoroughly ML-ERV, our solution to the problem described above.

3. Machine learning-based rental vehicle model

In this section, we will present ML-ERV, our machine learning model designed to estimate CO_2 emissions generated by vehicles in a rental fleet. This model aims at predicting CO_2 emissions prior to renting the vehicle. This section is organized as follows. First, it will describe the dataset used to build our model. Second, it will study the correlation between rental vehicle CO_2 emissions and the predictor variables. Third, it presents the machine learning algorithms used to build ML-ERV.

3.1. Data collection

We developed ML-ERV using Carbookr's bookings dataset (table 2). This dataset includes 26770 samples, and it contains input features and a corresponding output target. It consists of rental vehicle bookings made through Carbookr's platform in the period 2016-2023 and handled in accordance with privacy policies. Each record contains data regarding client identification (client refers to the company the driver works for), driver identification, user identification (user refers to the person who made the booking, it can be the driver himself or it can be someone working for the client company), vehicle information, travel information, invoice information, supplier information and invoice data. Table 2 shows the total number of variables contained in the dataset provided, along with the percentage of missing data and invalid data.

The records of bookings provided by Carbookr were subject to data cleaning. The criteria followed for data cleaning are the following. Eliminate variables that are not considered of interest for this study, get rid of variables with a high proportion of missing values, eliminate variables that make the analysis difficult, remove those that provide duplicate information, and

Table 2. Dataset description.

Dataset	Total number of records	Total number of variables	Percentage of missing values	Percentage of invalid records
Carbookr's bookings	26770	114	15%	32%

eliminate those used for the generation of new variables. Table 3 shows the descriptive statistics of the independent variables used to predict CO_2 emissions.

Table 3. Predictive variables of CO_2 emissions.

Variables	Description	Min	Max	Mean	Standard deviation
ACRISS (acriss)	Vehicle classification code	NA	NA	NA	NA
Mileage (mileage)	Traveled kilometers	0	40056	516.26	946.91
Duration (duration)	Rental duration (in half days)	2 (1 day)	300 (150 days)	8.1	10.2
Included mileage (incl)	Kilometers he can drive without incurring additional charges	0	23976	876.2	1121.83
Driver's country (dr_country)	Where he lives	NA	NA	NA	NA
Client's country (clt_country)	Where he works	NA	NA	NA	NA
Pickup country (pu_pl_country)	Where he took the vehicle	NA	NA	NA	NA
Return country (r_pl_country)	Where he returned the vehicle	NA	NA	NA	NA

Note that ACRISS (`https://www.acriss.org/car-codes/`) is short for Association of Car Rental Industry Systems and Standards. It assigns a code of four characters to each vehicle. The first character denotes the vehicle category. The second character defines the vehicle type and chassis type (van, SUV, wagon, convertible, etc.). The third character defines the transmission and drive – automatic / manual and 2WD / 4WD / AWD. And the fourth character defines the fuel type (petrol, diesel, hybrid, electric, etc.) and whether air conditioned or not.

Next, we will study the correlation between CO_2 emissions and the independent variables listed in table 3.

3.2. Correlation of rental vehicle CO_2 emissions and independent variables

Let's examine the correlation between the target variable (CO_2 emissions), which is a continuous variable, and the continuous predictors by measuring the Pearson's correlation coefficient; and between the target variable (CO_2 emissions) and the categorical predictors by means of the ANOVA test.

Table 4 summarizes the relationship between CO_2 emissions and continuous features. The results indicate a high positive correlation between the traveled distance and CO_2 emissions, and a moderate positive correlation between the included mileage and CO_2 emissions. The findings also show a low positive correlation between the rental duration and CO_2 emissions.

Table 4. Correlation values (continuous variables vs CO_2 emissions).

	Traveled distance	**Duration**	**Included mileage**
CO_2 emissions	0.73	0.45	0.6

Table 5 summarizes the relationship between CO_2 emissions and categorical features. The results indicate that the p-value for all categorical variables is less than the chosen significance level 0.05 which rejects the null hypothesis.

Table 5. Correlation values (categorical variables vs CO_2 emissions).

	ACRISS code	**Driver's country**	**Client's country**	**Pickup station country**	**Return station country**
CO_2 emissions	$1.34 \cdot 10^{-38}$	0.01	$9.69 \cdot 10^{-6}$	$7.389 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$

Traveled distance, included mileage and duration have a strong relationship with CO_2 emissions. Furthermore, the ACRISS code, the driver's country, the client's country, the pickup station country and the return station country have a great impact on CO_2 emissions. In this respect, the selected features are the traveled distance, the included mileage, the duration, the ACRISS code, the driver's country, the client's country, the pickup station country and the return station country.

3.3. Machine learning models

Decision trees, random forest, AdaBoost and XGBoost were fitted on the training dataset. The four models were compared based on performance metrics of predictive accuracy: coefficient of determination (R^2), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE). Table 6 summarizes the hyper-parameters used in the execution of each model.

In subsequent section, we will first describe the results obtained by each model, analyze and compare the findings. Then, we will compare ML-ERV to the state-of-the-art calculators.

4. Results and discussion

We will start with presenting the results of training and testing decision trees, random forest, AdaBoost and XGBoost on Carbookr's dataset. Then, we will describe the impact of each factor on the final predictions. Next, we will compare the results obtained by our model to the results obtained by the state-of-the-art calculators described in section 2.

4.1. Training and testing ML-ERV

The dataset was divided into two sets: one is the training data, which the machine learning algorithm uses for learning, and the other is the testing data, which is used to measure and compare the accuracy of the machine learning models. To identify the best split strategy, two proportions were used (70-30% and 80-20%). The training data and the testing data were defined

Table 6. Hyperparameters used in the execution of the models.

Model	Hyper-parameters description	Value
Decision trees	*max_depth*: the maximum depth of the tree	10
Random forest	*max_depth*: the maximum depth of the tree	10
	n_estimators: the number of trees in the forest	100
AdaBoost	*n_estimators*: the maximum number of estimators at which boosting is terminated	100
	base_estimator: the base estimator from which the boosted ensemble is built	Decision trees
	learning_rate: weight applied to each regressor at each boosting iteration	0.01
XGBoost	*max_depth*: maximum depth of a tree	10
	learning_rate : step size shrinkage in boosting	0.1
	n_estimators: the maximum number of estimators at which boosting is terminated	100
	objective: the learning task and the corresponding objective function	Squared error

by stratified sampling in order to help the response variable reach a balanced distribution in both sets. All four models are executed 20 times each, and the findings show consistency. The comparison in terms of the performance of the regression models were carried out using R^2, RMSE, MAE and MAPE. Table 7 presents the average results.

Table 7. Comparison of regression models.

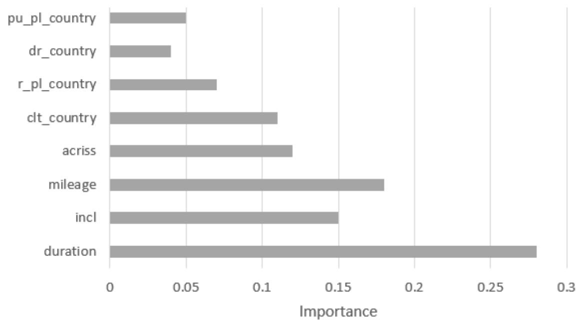
Model	80–20%				70–30%			
	RMSE	MAE	$\mathbf{R^2}$	MAPE	RMSE	MAE	$\mathbf{R^2}$	MAPE
Decision trees	1331.951	1177.816	0.497	0.088	1332.881	1178.511	0.496	0.088
Random forest	1200.741	1049.324	0.581	0.076	1202.445	1050.874	0.579	0.076
AdaBoost	1145.361	978.369	0.711	0.067	1147.256	979.185	0.71	0.067
XGBoost	1136.231	958.125	0.753	0.065	1137.587	956.224	0.752	0.065

The evaluation results show that there are no big differences with different training and test data proportions. The findings also indicate that the 80–20% proportion achieves better results than 70-30%. Therefore, the XGBoost has the better performance prediction compared to other models, which is clearly confirmed when the values of the evaluation metrics between the different models are compared in table 7, where the XGBoost has the highest R^2 value (0.753) and the lowest MAE (958.125), RSME (1136.231), and MAPE (0.065) values.

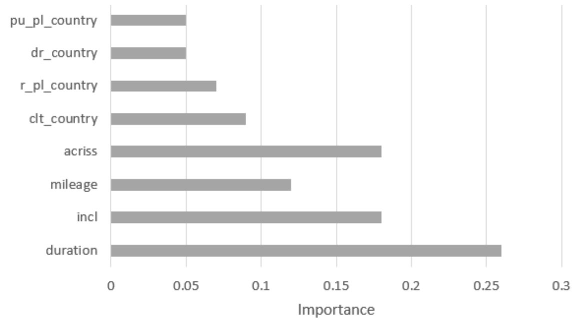
In the next section, we will show features importance for each single model through bar charts.

4.2. Variables importance

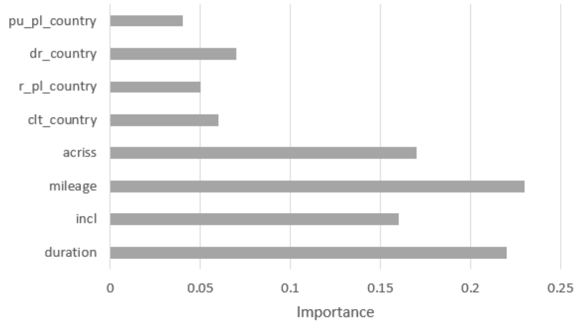
It is important to assess the variables' importance for each model through the permutation method in order to better understand how each model processes these variables to make predictions. This method determines the impact of features by measuring how much the model's performance decreases when the feature's values are randomly shuffled. Figure 1 illustrates the variable importance for each model.



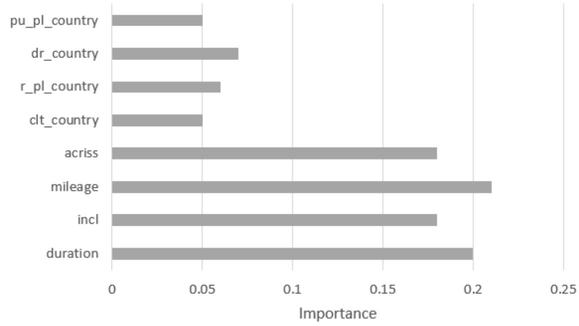
(a) Decision trees model



(b) Random forest model



(c) AdaBoost model



(d) XGBoost model

Figure 1. Features importance.

The four models select the features duration, mileage, included mileage and ACRISS code as very important variables, followed by driver's country, work country, country of the pickup station and country of the return station.

Next, we will compare the results obtained by ML-ERV against the existing calculators.

4.3. Comparing ML-ERV to the state-of-the-art calculators

Table 8 presents the results of applying each of the existing calculators shown in section 2 to the bookings dataset. The results (table 7 and table 8) indicate that ML-ERV achieves better results in terms of the evaluation metrics than existing calculators.

Table 8. Results obtained by the state-of-the-art CO_2 emissions calculators.

$\mathbf{CO_2}$ emissions calculators	RMSE	MAE	R^2
Equation (1)	1564.127	1487.457	0.37
Equation (2)	1678.118	1601.327	0.27
Equation (3)	1400.397	1315.742	0.39
Equation (4)	1497.738	1481.225	0.38
Equation (5)	1332.102	1228.575	0.4

In the next section, we will conclude this paper and present potential future research directions.

5. Conclusions and future research directions

This paper has critically reviewed the state-of-the-art CO_2 emissions calculators and showcased their key limitations in the rental vehicles industry. It then introduced ML-ERV, a new machine learning-based solution, to predict CO_2 released from rental vehicles prior to their usage. ML-ERV is designed to align with the rental vehicles' unique requirements.

ML-ERV was developed based on Carbookr's extensive booking dataset. Through an analytical exploration of the dataset, some correlations were identified between CO_2 emissions and the following variables ACRISS code, traveled distance, included mileage, duration, country of the pickup station, country of the return station, driver's home country and the country where the driver works. This research study used four machine learning models: decision trees, random forest, AdaBoost and XGBoost. The models were optimized by determining the best values for different hyper-parameters. The evaluation of the models via the metrics R^2, RMSE, MAE and MAPE indicates that XGBoost has the best prediction performance, and that our model ML-ERV trained using XGBoost reaches better accuracy than the existing calculators.

While our findings present a substantial leap forward, there remain avenues for further exploration and improvement. Future research work includes the development of user profiling models based on the booking dataset along with external data sources, leveraging such insights to enhance both ML-ERV's accuracy and adaptability to diverse user needs. Furthermore, incorporating additional rental vehicle-related features such as the vehicle model and the registration number holds promise for refining CO_2 emission predictions and ensuring the continued relevance of ML-ERV in a rapidly evolving industry landscape.

Beyond its immediate implications for CO_2 emissions monitoring in rental vehicles, our research work contributes to broader discussions surrounding sustainability efforts, technological innovation, and the optimization of transportation systems. By continually refining and expanding upon ML-ERV's capabilities, we aim to catalyze positive change within the rental vehicle industry and advance towards a more sustainable future.

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Seismic hazard assessment in the Shamkir-Mingachevir reservoir region through ground response analysis

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Seismic hazard assessment in the Shamkir-Mingachevir reservoir region through ground response analysis

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Abstract. This research addresses the imperative task of effective disaster mitigation planning for significant earthquakes, specifically focusing on the Shamkir-Mingachevir reservoir region. The complexities of seismic risk assessment involve the intricate interplay of geological, geotechnical, and environmental factors. The character of propagation of seismic waves is influenced significantly by local site conditions, shaping the observed intensity of ground motions at the surface. The term "site effects" is central to this research, signifying the amplification of seismic waves influenced by distinctive geological conditions. The results indicate that soils with lower shear wave velocities exhibit lower peak ground accelerations at the surface. However, the study highlights the susceptibility of softer soils to nonlinear effects, emphasizing the need to consider the composition of local soils in developing seismic safety measures. The separate study of resonant frequencies of the soil-structure system is crucial to mitigate resonant effects during earthquakes. This approach facilitates the development of accurate and tailored building standards aimed at safeguarding infrastructure and ensuring safety in seismic zones.

1. Introduction

To effectively address disaster mitigation planning for significant earthquakes, it is crucial to conduct thorough assessments of ground motion intensities and potential building damage resulting from hypothetical seismic events. The complexities of seismic risk assessment involve not only the magnitude and depth of earthquakes but also the intricate interplay of geological, geotechnical, and environmental factors. The observed intensity of ground motions at the surface is influenced by source effects, path effects, and, notably, site effects [1, 2]. Evaluating site effects is crucial because surface soil characteristics can lead to significant amplification of ground motion during seismic events, posing a heightened risk of severe damage to buildings, infrastructure [3], and potential loss of lives.

The recognition that local site conditions play a pivotal role in the propagation of seismic waves has been consistently affirmed through extensive earthquake studies, has found broad application in practical engineering [2, 4–12], and has stimulated comprehensive theoretical investigatins [1, 13–15].

Seismic waves undergo modifications influenced by local geological conditions. Seismic site effects are intricately linked to the amplification of seismic waves in superficial geological layers. In a broader context, the term "site effects" encompasses the amplification of seismic waves resulting from specific geological conditions. Site effects stem from various physical phenomena, including multiple reflections, diffraction, focusing, and resonance, all of which impact the incoming wave front.

A notable illustration of this phenomenon occurred during the 1985 Michoacan earthquake in Mexico City [16]. Surprisingly, peak ground accelerations (PGAs) were more pronounced at 400 km from the epicenter than at the epicenter itself (figure 1).

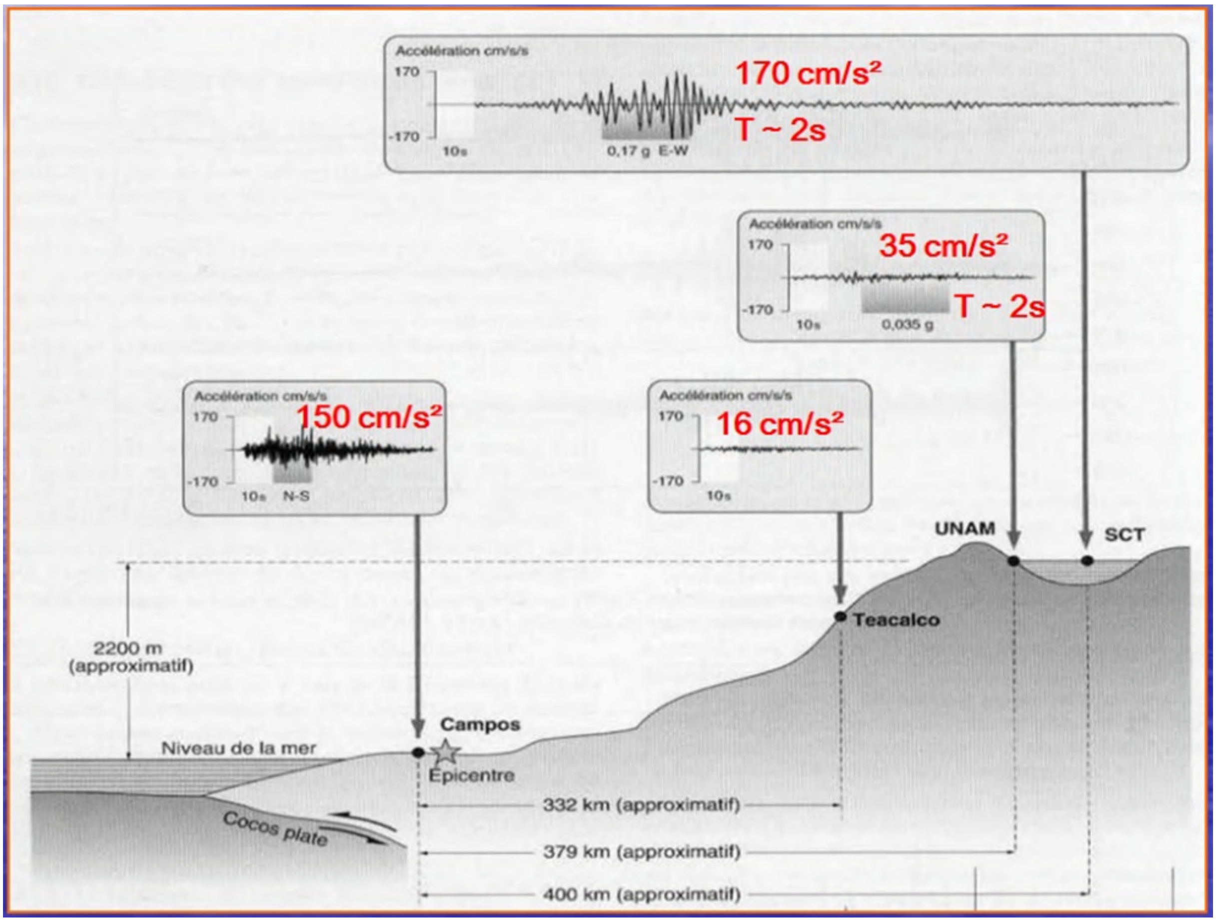

Figure 1. Example of seismic site effects [3, 16].

This unusual occurrence was attributed to the amplifying effect of the soft sediments underlying the region. Despite the earthquake's epicenter being approximately 400 km away, the seismic motions experienced in Mexico City were significantly intensified. The amplification reached a factor of 60 compared to the bedrock, primarily due to the presence of soft clay deposits beneath the city [9]. This case underscores the critical role of local geological conditions in shaping ground motion intensities during seismic events.

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2. Research aim and objectives

These studies deal with advanced examination of seismic hazards within the Shamkir-Mingachevir reservoir region, which is a critical area where significant hydroelectric infrastructure is located. The investigation is prompted by the imperative need to understand the seismic dynamics of this region, particularly due to the presence of essential hydroelectric power stations (HPSs). The term "site effects" is key to our research, signifying the amplification of seismic waves influenced by distinctive geological conditions. The intricate relationship between seismicity, the response of local soil conditions, and the crucial hydroelectric infrastructure in this region underscores the importance of this study in contributing to effective disaster preparedness and risk mitigation strategies.

3. Seismicity in Azerbaijan and the Shamkir-Mingachevir reservoir region

The Azerbaijan territory, as a part of the Alpine folded system, is characterized by very high seismic activity. Throughout history, the region has experienced strong and catastrophic earthquakes leading to significant human losses and widespread destruction.

Among the areas heavily affected, it is worth noting the Shamakhi and Ganja regions, where some of the most powerful earthquakes were occurred [17, 18]. The earthquake in Shamakhi in 1668, with a magnitude of 7.0 and an intensity of 9-10 points, is considered one of the strongest earthquakes in the Caucasus. Historical records indicate that this event triggered landslides resulting in the tragic loss of over 80,000 lives.

Shamakhi continued to experience seismic activity with intensities reaching up to 8 according to MSK-64 in the years 1828, 1859, 1869, and 1872. The last catastrophic earthquake in this region, with a magnitude of 6.9 and an intensity of 9 points, occurred in 1902.

Another region affected by destructive earthquakes is Ganja, where significant seismic events took place in 427 (magnitude 6.7, intensity 9 points), 1139 (magnitude 6.8, intensity 9 points), and 1235 (magnitude 5.7, intensity 8 points). The earthquake in 1139 led to the creation of Goy-gol Lake due to landslides.

Various other regions of the republic have also recorded numerous strong earthquakes, with intensities ranging up to 6-7 points. While the intensity may not have been as extreme, these seismic events often resulted in substantial destruction. The historical seismicity of Azerbaijan underscores the importance of ongoing seismic risk assessment and disaster preparedness efforts in the region.

In this research, we examine the seismic activity in Azerbaijan spanning the years 1973 to 2023 utilizing data sourced from the US Geological Survey (USGS) [19]. Figure 2 displays the locations of earthquakes with magnitudes exceeding 3 that occurred during this period providing a visual representation of the seismic events in the region.

Considering the statistical properties of these earthquakes, we evaluate the histograms for earthquake magnitudes and depths. In particular, figure 3a shows the earthquake magnitudes histogram approximating the corresponding *unimodal* distribution of earthquake magnitudes.

The earthquake magnitude distribution indicates that most events in Azerbaijan occur with a magnitude of 4-4.5 (almost 42%). Earthquakes with a magnitude greater than 5 are less than 17%, and those greater than 6 are less than 1%.

Doing in the similar manner, the histogram for earthquake depths is evaluated and depicted in figure 3b. It is worth to note that, in contrast to the magnitude histogram, the histogram for depths quite confidently tends to a *multimodal* depth distribution of earthquakes. The depth distribution analysis underscores a predominantly crustal nature of seismic events in Azerbaijan. Almost all earthquakes are concentrated at depths of less than 50 km, with the majority occurring at depths of up to 25 km. This pattern suggests that the seismic activity in the region is primarily associated with crustal tectonic processes.

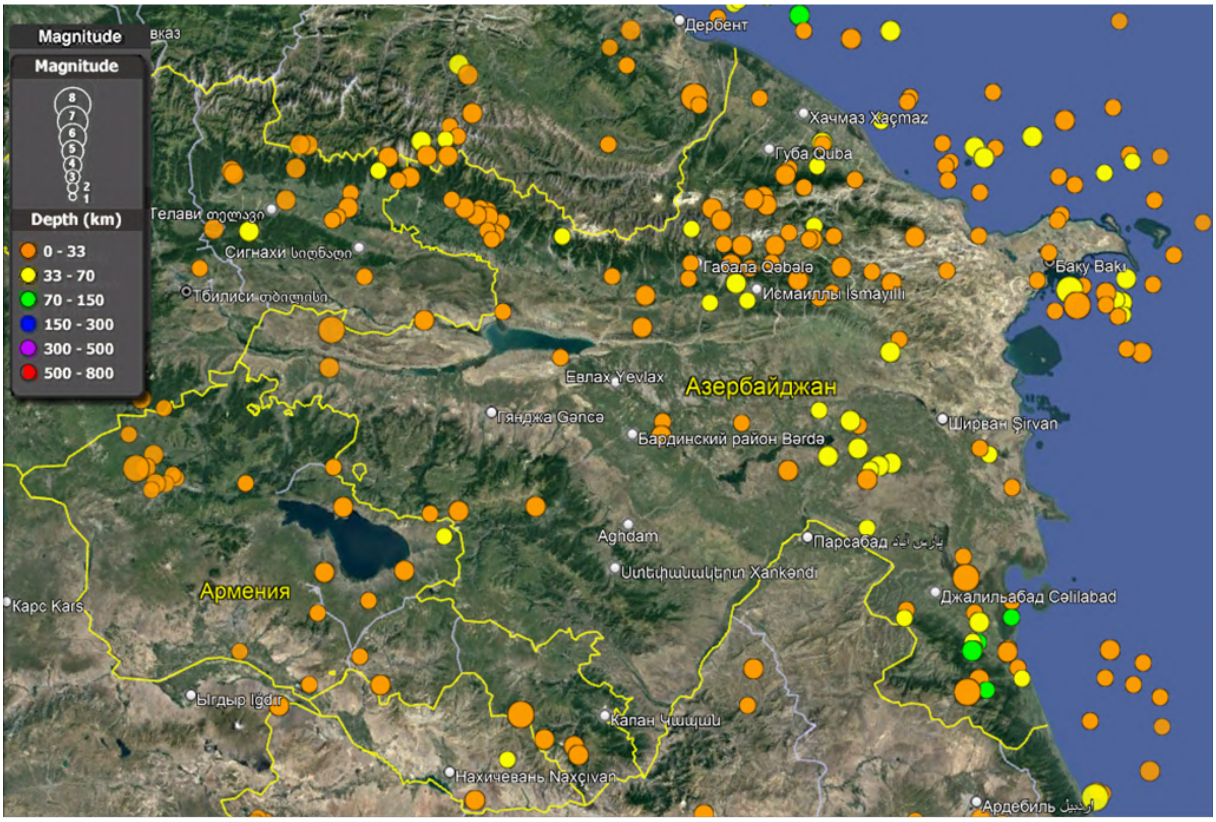
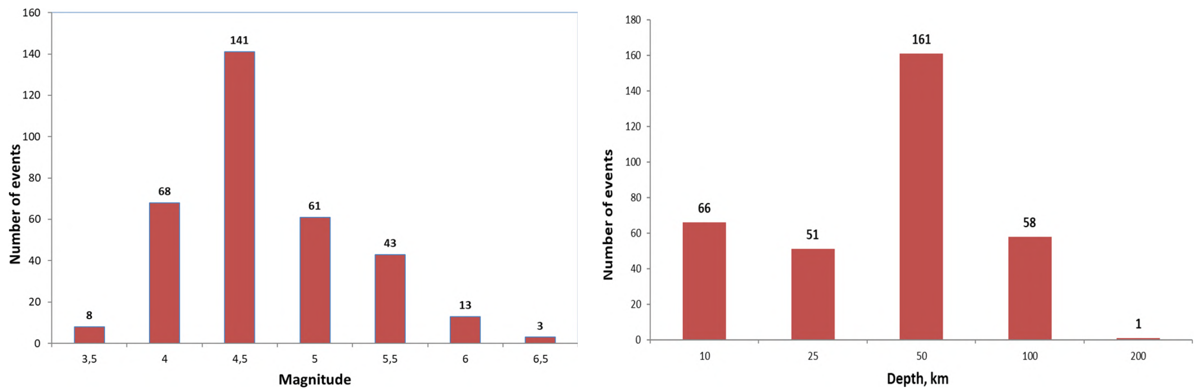


Figure 2. Earthquakes with magnitudes exceeding 3 observed in Azerbaijan from 1973 to 2023.



(*a*) (*b*)

Figure 3. Magnitude and depth distributions of earthquakes exceeding 3 occurred in Azerbaijan from 1973 to 2023.

Analyzing data mentioned above, we also reveal a notable trend – earthquakes tend to occur with higher frequency in proximity to HPS in Mingachevir compared to the Shamkir HPS. Most earthquake epicenters, as recorded by the USGS, are situated within the 25-150 km range from the Mingachevir HPS. In contrast, over 50% of seismic events occurred at distances exceeding 150 km from the Shamkir HPS. On average, the distance from the Mingachevir HPS to earthquake epicenters is approximately 150 km, while for the Shamkir HPS, this distance extends to 225-250 km.

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4. Seismic site effects of the Shamkir-Mingachevir reservoir region

We conducted an in-depth examination of the seismic activity in the Shamkir-Mingachevir reservoir region, with a particular focus on the response of surface soils at the Mingachevir and Shamkir HPSs during seismic events. Recognizing the crucial role of near-surface soils in amplifying the propagation of earthquake waves from bedrock to ground level, our study delved into the intricate details of this phenomenon. Our analysis utilized seismic data from USGS and applied ground response analysis techniques to comprehensively assess the potential impact of seismic motions on these vital infrastructures.

Seismic site response analysis is used to assess the effect of site-specific soil conditions on expected earthquake ground shaking. Our research focused on modeling the impact of the upper 30 meters of local soils at the Mingachevir and Shamkir HPSs in response to seismic impacts of different amplitudes. We used accelerogram records on bedrock with maximum amplitudes ranging from 0.05g to 0.33g as seismic impacts. These amplitude values correspond to the expected levels of seismic activity that could affect the territory of the Mingachevir and Shamkir HPSs, in accordance with preliminary studies of seismicity in Azerbaijan.

In our initial examination of seismic activity in Azerbaijan, we have concluded that earthquakes with a magnitude of approximately 4.5 are the most prevalent in the region. However, establishing a direct correlation between earthquake magnitude and the amplitude of surface vibrations proves elusive. The amplitudes of seismic motions at the surface are influenced by various factors such as the distance from the earthquake source to the site, the orientation and direction of fault rupture, site-specific conditions, and more.

Recognizing the multifaceted nature of these influences, we have adopted a comprehensive approach by considering a broad spectrum of potential maximum amplitudes of seismic vibrations on bedrock. This inclusive strategy aims to account for the diverse array of factors that can impact seismic activity and ensures a thorough assessment of the associated risks. We applied the one-dimensional equivalent linear method to assess the effect of the upper 30 meters of soil conditions at the Mingachevir and Shamkir hydroelectric power stations on changes in the amplitude-frequency composition of seismic vibrations during an earthquake.

Site response analyses utilizing the equivalent-linear approach incorporates nonlinearity in soil behavior by employing curves for modulus reduction and damping that are dependent on strain. The calculations for the equivalent-linear approach were conducted using the ProShake program [20].

The part of the map presented in figure 4 illustrates the V_s^{30} distribution, i.e., the distribution of average shear wave velocity for the upper 30 meters of soil in the specified area. This data is extracted from the USGS resource [21] and visualized with the help of tools offered by [22]. In addition, the data serves as crucial input for modeling seismic site response analysis. Signifying its paramount importance, this parameter stands as the key input for evaluating the seismic response.

From the analysis of V_s^{30} values it follows that the regions neighboring Mingachevir HPS exhibit lower velocities compared to those in proximity to Shamkir HPS. This observation suggests that, from a seismic standpoint, the soil conditions at Mingachevir HPS are less favorable than those at Shamkir HPS. The presence of a low-velocity upper 30-meter soil layer at Mingachevir HPS implies a higher susceptibility to nonlinear effects and potential stability issues during seismic events.

5. Results and Discussion

Figures 5(a)-(d) illustrate the computed variations in bedrock motion peak ground accelerations at the Mingachevir and Shamkir HPSs' surfaces. These variations are associated with soil effects within the upper 30 meters, considering maximum amplitudes of 0.05g, 0.1g, 0.19g, and 0.33g.

Figures 5(a)-(d) highlight a noticeable rise in PGA at the surface compared to the initial

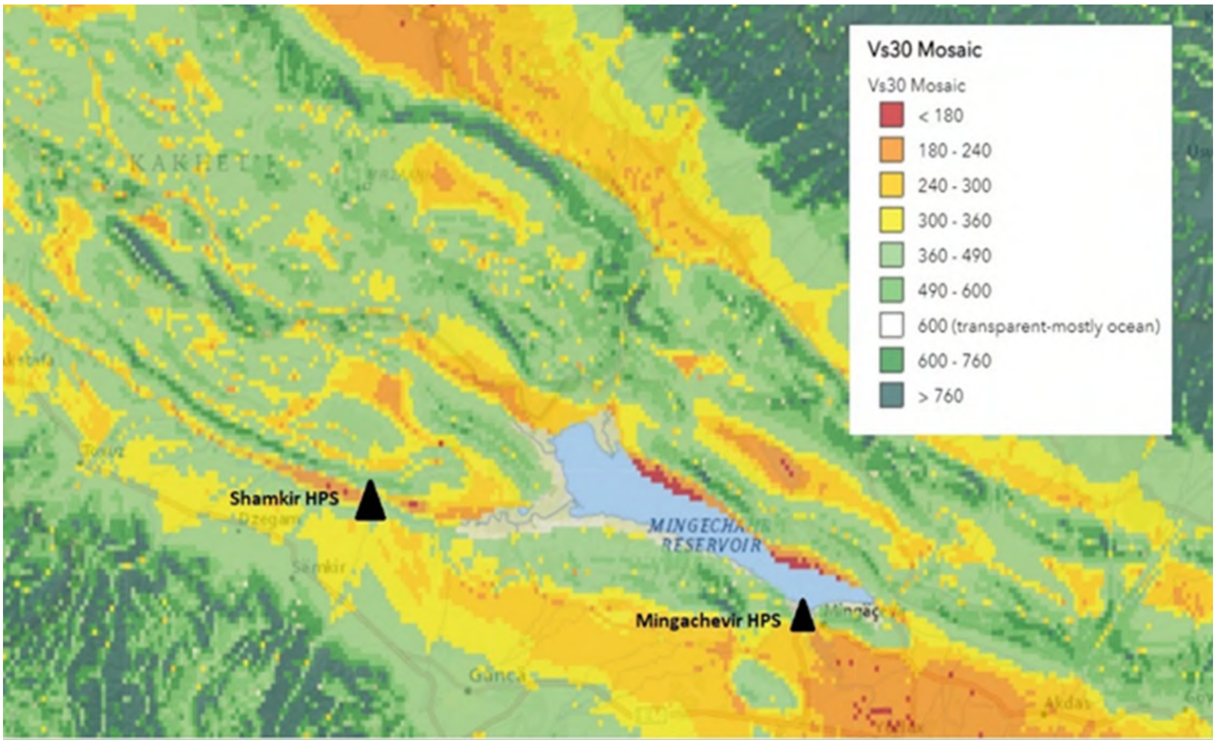

Figure 4. The V_s^{30} map of Shamkir and Mingachevir HPSs and adjacent areas.

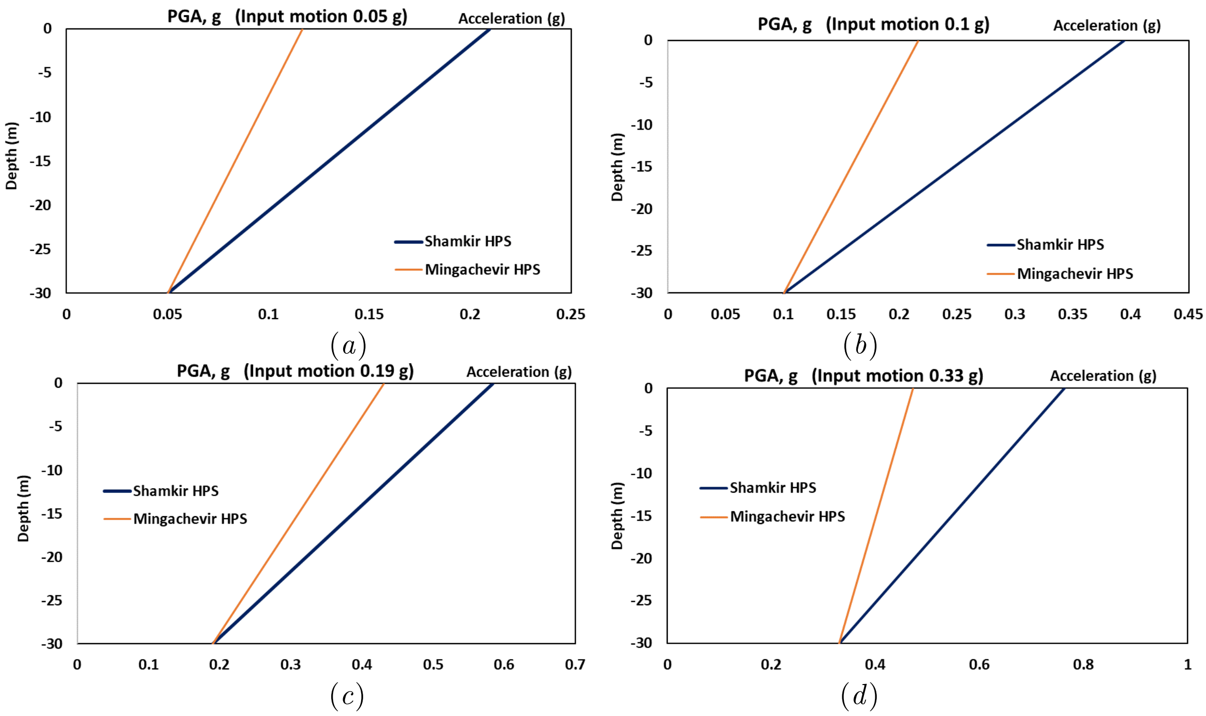

Figure 5. Variation in PGA from the bedrock to the surface along the top 30 m of soil for different input motion amplitudes: 0.05g (a); 0.1g (b); 0.19g (c); 0.33g (d).

PGA from the bedrock motion. More deep examination of these dependencies allows us to conclude that in all cases the PGA of seismic vibrations increases within the upper 30 meters of the soil. Notably, the Shamkir HPS site exhibits a more pronounced surge in PGA compared to the Mingachevir HPS site when a seismic wave passes through the upper 30-meter soil layer. This observed effect is presumably linked to a greater increase in the seismic energy absorption coefficient within the lower-velocity soil layer at the Mingachevir HPS site, as opposed to the case of the Shamkir HPS site.

Figure 6 displays the calculated transfer functions for the upper 30 meters of soil at the Mingachevir and Shamkir HPSs. The transfer function, a crucial parameter in soil response analysis, essentially dictates how each frequency in the bedrock motion (input) is either amplified or attenuated by the soil sediments [1]. Conceptually, a transfer function can be likened to a filter, influencing an input signal to generate a corresponding output signal.

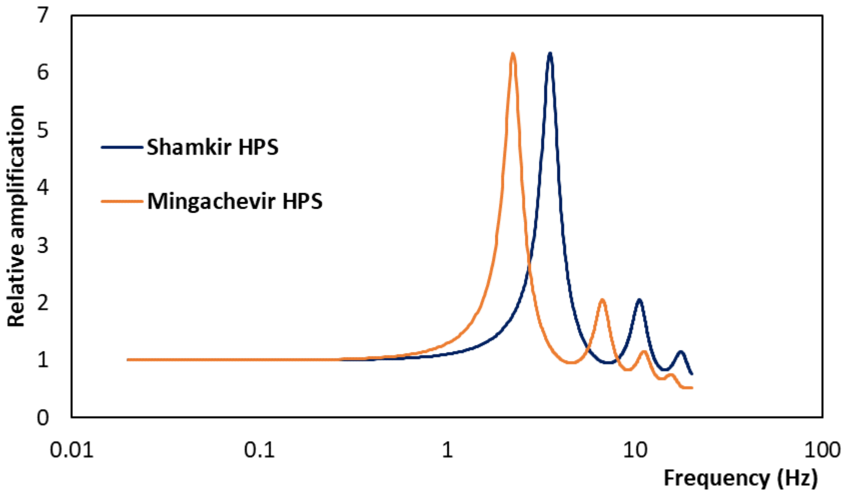

Figure 6. The transfer functions for 30 m deep soil profiles at the Mingachevir and Shamkir HPSs.

As illustrated in figure 6, both sites prominently exhibit amplified seismic motion owing to their near-surface geology. While the transfer functions generally align, distinctive peaks emerge at varying frequencies, signifying the potential for resonant amplification of seismic motions, nearly reaching a factor of 7. However, upon closer inspection, a nuanced analysis unveils unique resonant amplifications occurring in different frequency ranges, emphasizing the diverse seismic characteristics inherent to each location.

Examining the Mingachevir HPS site, the soil predominantly amplifies seismic motions at lower frequencies, manifesting resonant amplifications within the frequency range of 1.8-2.68 Hz. A particularly noteworthy peak occurs at 2.28 Hz. In contrast, the soils at the Shamkir HPS site exhibit a tendency to amplify seismic motions at higher frequencies, displaying resonant amplification within the frequency range of 2.84-4.22 Hz. The pinnacle of resonant amplification at this site is observed at 3.56 Hz.

Thus, the study's findings underscore a divergence in the seismic behavior of surface soils between the Mingachevir HPS and Shamkir HPS areas. Specifically, at the Mingachevir HPS site, worst-case scenarios are projected to be associated with low-frequency seismic motions. Conversely, in the Shamkir HPS section, a predisposition for more adverse scenarios linked to higher-frequency seismic motions is anticipated compared to the Mingachevir HPS site. This distinction emphasizes the imperative need to tailor seismic risk mitigation strategies based on the unique characteristics of each site.

6. Conclusions

The conducted studies highlight the crucial influence of upper near-surface soils on the dynamics of seismic motions during their propagation from bedrock to the free surface. The results indicate that soils with lower shear wave velocities, due to greater seismic energy absorption, exhibit lower PGA at the surface. However, it is imperative to acknowledge that softer soils are susceptible to nonlinear effects, and despite the observed decrease in PGA values, this does not imply seismic stability of the soil. On the contrary, with an increase in the absorbing properties of the soil, the probability of nonlinear deformation of the soil increases, which, in turn, depends on the amplitude of seismic loading. Thus, the nonlinearity of the soil, during seismic impact on the site, mainly leads to a decrease in the resonant frequency of the site and a decrease in the amplification at high frequencies (for instance, PGA) but an increase in the amplification of vibrations at low frequencies.

The soils of the Mingachevir HPS, initially characterized by lower values of V_s^{30} compared to the soils of the Shamkir HPS, exhibit resonant maxima at lower frequencies as a result of a comparative analysis of transfer functions. It is important to note that as soil softness increases, high frequencies are damped while low frequencies are enhanced. Given that most above-ground buildings have a resonant frequency in the range of 2-10 Hz, soils with a tendency to amplify lower frequencies (10 Hz or less) may have a more significant impact and cause serious vibration damage.

In summary, to enhance our understanding of the seismic impact and to develop effective seismic safety measures, it is advisable to consider not only the overall amplitudes of vibrations but also the specific characteristics of the soil, which selectively amplifies seismic vibrations at certain frequencies. Furthermore, a crucial aspect involves individually studying the resonant frequencies of the soil-structure system to mitigate resonant effects during an earthquake. We also believe that this approach will allow one to develop more accurate and tailored building standards aimed at protecting infrastructure and ensuring safety in seismic zones.

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Evaluation of the green flood mitigation measures in urban area in the frame of the sustainable city concept

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Evaluation of the green flood mitigation measures in urban area in the frame of the sustainable city concept

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Abstract. The flood protection problem has always existed for the Ukrainian Carpathians. The floods that caused damage to urban areas occurred 10 times during the past 20 years in the basin of the Uzh River, ones were the cold period floods in most cases. The Uzh River passes through the central part of the Uzhhorod city, the river is crossed by five bridges, the embankment consists of "grey" flood protection structures: dams, concrete and stone walls. The central embankment was flooded by extreme floods only. At the same time auxiliary buildings and greenhouse in the Botanic Garden and the Bozdos Park area are flooded almost every two-three years. The purpose of the work is to update hydrological calculations, to calculate the flood water surface curve and assessment of the "green" flood mitigation measures in the central part of the city. Flood flow rate of 1% probability was calculated by processing continuous observations data for 72 years. Flood water levels of 1% probability were calculated using a 1D HEC-RAS model. Retention reservoirs, old river bed, mobile flood protection systems for local areas and buildings were considered as "green" flood control measures. Relocating embankments to make "room" for river within the existing buildings is not possible, but some stream widening has been preserved within the Botanic Garden by local flood protection of the single buildings and the central part of the garden. Calculation showed that the central part of the city is protected from flooding by the existing dykes, except for a few areas that would be protected by local mobile barriers. It is not possible to create an exclusively "green" flood control measures in the urban area, but the further development of flood risks management must be directed to the concept of a sustainable city development with minimization of the negative environment impact.

1. Introduction

The problem of hazard floods has always existed for the Ukrainian Carpathians. The frequency and flow rate of floods has been increasing over the past 20 years. The both natural phenomena associated with climate change [1] and the population economic activity, which mercilessly exploited nature and the water environment in the last century, became the reason for the flood risks increasing. Mountain areas are particularly sensitive to climate change, as research shows, these areas will be subject to extreme floods in the future and the amount of flood flow rate tends to increase [2]. Therefore, the problem of protecting settlements from extreme floods remains relevant and is an integral part of the concept of a sustainable city.

The history of flood control management includes different periods and corresponding approaches to flood protection. In the past, the population that settled along the river banks tried to choose elevated area. Population growth led to the building on the floodplains, people settled closer to the water and periodically suffered from flooding. In the article [3] is indicated the development of urban infrastructure, solid waterproof coverings, storm sewers lead to the temperature and flood flow rate increasing on the urban territory. Flood protection traditional method is dyke and walls construction that narrow the floodplain and channelize the river bed. Canalization of the river leads to the water speed increasing, erosion and increasing the flood flow downstream [4].

Sustainable Development Goals (SDGs) require other approaches to protect against extreme floods, which have received the term "green" measures in the literature. The modern approach requires the floodplain restoration and usage of its retention capacity [5], an expansion of the room for overflowing the flood flow, which leads to a lag time in reaching the river bed due to the natural cover, and peak flow reduction. Restoration of the floodplain in some catchments allows to significantly reduce the peak flow [6]. At the same time, the territories in the countryside are occupied by agriculture and it is not always possible to create conditions for the free flood flowing along the floodplain. Increasing the roughness of the river bed contributes to a lag time when the flood flow is running downstream. Calculations in the work [7] showed that vegetation cover with and creating berms on the river banks allows to reduce the water speed and erosion of the banks and decrease the flood flow downstream.

In the conditions of the existing infrastructure, agricultural fields and housing, it is not always possible to allow the river bed to freely meander and overflow. In work [8], instead of strengthening the banks of the main channel, it was proposed to use the old channels of the Czarny Dunajec River, Polish Carpathians. Environment-friendly measures allowed enhanced ecological functions of the multithread channel and the natural variability.

The most significant flood flow reduction is possible due to the retention capacity of the floodplain. In work [9], analysis of flood mitigation measures using dry and wet retention reservoirs on the Glinscica River catchment (Slovenia) were carried out. Calculations using HEC-RAS showed that retention reservoirs can provide a significant decrease in peak flow, but the decrease in water levels during a flood is local and reservoir effects quickly reduce with scale. The cost of building retention reservoirs is quite high and may exceed the potential benefits. It is obvious that the implementation of flood reservoirs requires their multifunctional use. At the same time, Bezak et al. [9] notes that afforestation as a sole flood protection measure is not effective for larger flood flow.

In a mountainous area, the formation of floods is fast and the peak flow are significant, so the use of retention reservoir is an effective method, if there are the natural depressions of sufficient volume to located near the protected settlement. But there are not always favourable conditions for the construction of such reservoir. Pudar et al. [10, 11] analysed the improvement of the existing "grey" infrastructure (dykes) with the possibility of introducing "green" measures (retention reservoirs) on the upper watershed of the river Tamnava and its tributaries Gracica and Ub, in central Serbia in rural and urban areas and offered a holistic, integrative approach that includes both types of infrastructure.

Green measures for sustainable development of cities are developed in the direction of increasing the time of rainwater runoff into the river and the spread of green zones due to the creation of roofs with vegetation, vertical vegetation (green facades), vegetation elements in the area, trees and tree lines, artificial wetlands, permeable and semi-permeable grassed land cover [12]. Bezak et al. [9] assessed the possibility of using Permeable Concrete as a road cover, which transfers surface rainwater runoff into the underground, due to which the lag time increases. The article also notes that, unfortunately, the implementation of such an initiative is quite expensive and can be used in new construction, and it is also noted that the use of retention reservoir is much more efficient. Hamin and Usman [13] studying the green infrastructure noted that increasing the area of parks and green spaces, arranging 30 m and 100 m free bank area reduces the flood flow, but not significantly, up to 2.5 %. Also, works [14, 15] note the positive effect of the introduction of “green” infrastructure as rainwater harvesting and the increase of green areas in the city, but these measures cannot solve the problem of protection against extreme floods, because the flood flow of the river basin significantly exceeds the local flow of rainwater.

Mobile flood control systems do not belong to “green” measures and “green” infrastructure, they manage water, but do not contribute to the restoration of natural ecosystems. On the other hand, these systems are installed temporarily during extreme floods, so they do not have a negative impact on the ecosystem in other periods [16–18]. Mobile flood control systems can be classified as flood measures that helps to achieve sustainable development goals.

The aim of the work is to update hydrological calculations, to assess flood risks on the urban territory and to develop an environmentally friendly “green” flood mitigation measure.

2. Materials and methods

2.1. Study area

The Uzh River is a left tributary of the Laborets River (Slovakia) and belongs to the Danube basin. The length of the river is 128 km, the catchment area is 2750 km^2 (within Ukraine, respectively, 107 km and 2010 km^2), the total level drop is 775 m, the average slope is 0.0072.

Floods in the river basin are observed both in the summer and in the cold period, the height of the water rise is 1.5-2.0 m and 2.5-3.0 m in years of high water with the intensity of the water rise of 2.2-3.0 m/day. The rain floods of warm period are observed with maximum flows significantly lower than cold period floods. In total, the Uzh River basin is monitored at 7 gauging stations with duration of up to 20 years and 5 gauging stations with observation period of more than 50 years (figure 1). The cold floods are of mixed origin, i.e. formed as a result of intense snowmelt and torrential rainfall. Extreme floods were observed in 1926, 1955, 1957, 1968, 1992, 1998, 2001, 2005, 2008, 2010, 2015, 2016, 2017, 2019, 2023. The highest flood occurred on December 14, 1957, the flow reached 1680 m^3/s, the extreme flood of the last 20 years occurred on November 17, 1992 with a flow rate of 1280 m^3/s.

Study area is central part of the Uzhhorod city between gauging station and bridge along Babyak street (figure 1). The riverbed has a trapezoidal shape with a berm in the form of a footpath and is covered with grass, near the bridges the banks are strengthen by stone walls. The Uzh River floodplain is limited on both sides by dykes (figure 1), designed for flood of 1% probability, except the dyke along Bozdos Park, which is built at the level of 10% flood flow and has several damages. There are five bridges across the river. During floods, the territory of Bozdos Park is flooded almost every two-three years: November 2016, December 2017, December 2020, January 2023.

2.2. Study methods

In this research, the analysis procedures involve following steps: hydrological analysis, hydraulic analysis and environmentally friendly “green” flood control measure.

To determine the main characteristics of the flood runoff of the Uzh River, the materials of long-term observations of the city of Uzhhorod gauging station (the beginning of observations is 1947) were used. The catchment area calculated by QGIS and SAGA GIS is 1976 km^2. The estimation of the statistical parameters of the analytical flow duration curve was performed by the grapho-analytical method [19], the following equation were used:

$$S = \frac{Q_5 + Q_{95} - 2Q_{50}}{Q_5 - Q_{95}}, \tag{1}$$

$$\sigma = \frac{Q_5 - Q_{95}}{\Phi_5 - \Phi_{95}}, \tag{2}$$

$$\overline{Q} = Q_{50} - \Phi_{50} \cdot \sigma, \tag{3}$$

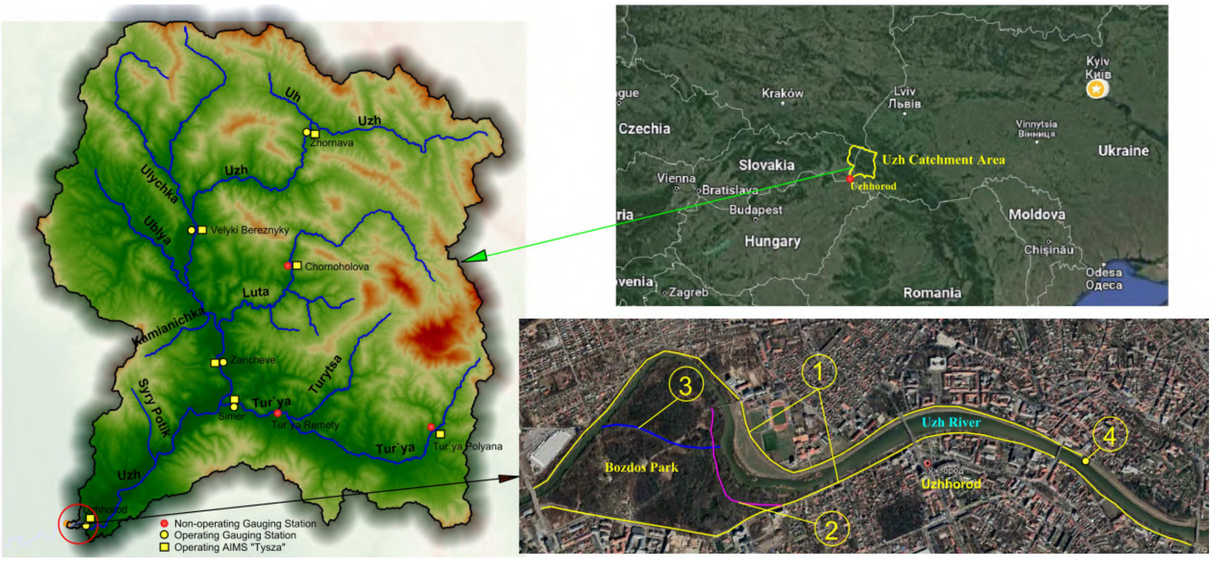

Figure 1. Study area: 1 – dyke 1% probability; 2 – dyke 10% probability; 3 – old river bed; 4 – gauging station Uzhhorod; yellow circle – operating gauging station; red circle – non-operating gauging station; yellow square – operating AIMS "Tysza".

$$C_v = \frac{\sigma}{\overline{Q}}, \tag{4}$$

where S – skew coefficient of the flow duration curve; Q_5, Q_{50}, Q_{95} – flow rate of probability, respectively, 5%, 50%, 95%, m^3/s; Φ_5, Φ_{50}, Φ_{95} – standard deviation from the mean value of the ordinates of the log-normal distribution of the flow duration curve; σ – mean square deviation; $\overline{Q}$ – mean flow rate, m^3/s; C_v – coefficient of variation.

The values of the statistical parameters of the cold flood on the Uzh River on the base of the observation of the Uzhhorod gauging station are given in table 1.

Table 1. Statistical parameters of the cold flood in the site of the Uzhhorod gauging station.

Catchment area, km^2	Flow rate of 1%, m^3/s	Flow rate of 50%, m^3/s	C_v
1976	1844	461	0.55

As the model of the hydrograph of the flood 1% probability was taken the flood hydrograph with mean daily flow of the flood dated on November 16-24, 1992 (figure 2).

The calculation of the flood hydrograph of 1% probability was carried out using transition coefficient [19]:

$$K_Q = \frac{Q_1}{Q_M}, \tag{5}$$

$$K_t = \frac{q_M}{h_M} \cdot \frac{h_1}{q_1}, \tag{6}$$

where Q_M, Q_1 – the peak flow of flood, respectively, of the model hydrograph and the hydrograph of 1% probability, m^3/s; q_M, q_1 – specific flow, respectively, of the model hydrograph and the hydrograph of 1%, $m^3/s{\cdot}km^2$; h_M, h_1 – runoff layers of the model hydrograph and the hydrograph of 1%, mm.

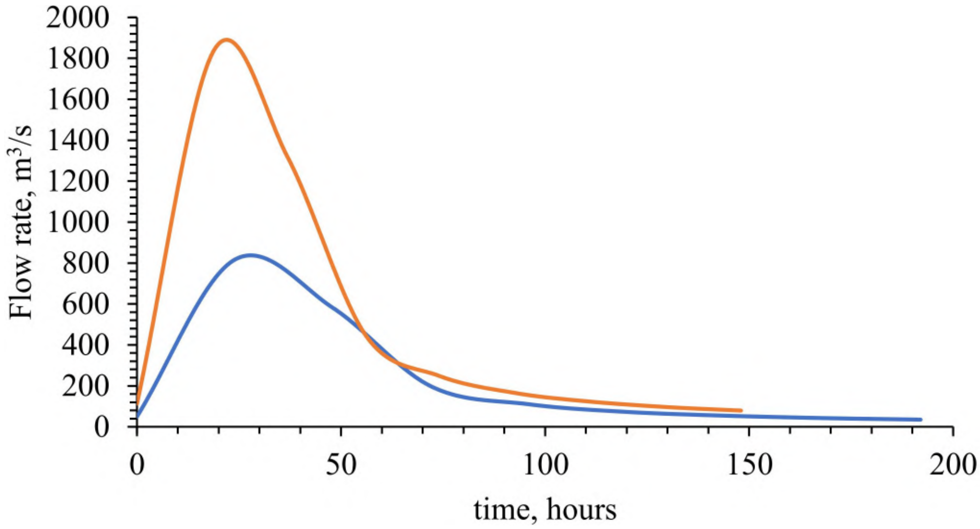

Figure 2. Hydrograph of extreme flood in 1992 and flood 1% probability: blue line – flood hydrograph of 1992; red line – flood hydrograph of 1% probability.

The coordinates of the hydrographs of 1% are calculated according to the equation:

$$Q_i = Q_{i,M} \cdot K_Q, \tag{7}$$

$$t_i = t_{i,M} \cdot K_t, \tag{8}$$

where $Q_{i,M}$, Q_i – peak flow at i-th time, respectively, for the model hydrograph and the hydrograph of 1% probability, m^3/s; $t_{i,M}$, t_i – time, respectively, for the model hydrograph and the hydrograph of 1% probability, hours.

Hydraulic calculations of the flood level of the 1% probability were carried out using HEC-RAS software complex for the 1D flow model. The basis of the calculation is the digital model of the area in the form of cross-sections, which are tied along the length of the river channel (figure 3) and bridges. The cross-sections were made instrumentally, as the cross-sections that can be obtained from free-access satellite images with a resolution of 30 m do not reflect the surface under water and often incorrectly reflect the position of the embankment (figure 4). Since the distance between the sections affects the calculation results [20], the sections are located perpendicular to the channel line at an average distance of 150-200 m.

The surface roughness data for the model were taken according to the analysis of land cover in the channel and banks of the Uzh River (figure 3). The bottom of the Uzh river is uneven, with large stones and pebbles. The channel in the central part of the city is channelized, limited by dikes with grass vegetation. The dyke crests are embankments with pavements, trees and bushes are planted on the edges, there are no parapets. Buildings located near the pedestrian zone.

The 1D flood simulations based on St. Venants continuity equation, which describes the preservation of mass in a given control volume. The upstream boundary condition is 1% flood flow rate, downstream model boundary is a normal depth-type condition with the hydraulic slope calculated from the average slope of the historical flood in 1992.

The calibration of the model and the determination of the calculated values of the Manning's values took place according to the flow curve at the Uzhhorod gauging station and using the historical flood in 1992 with flow rate of 1280 m^3/s.

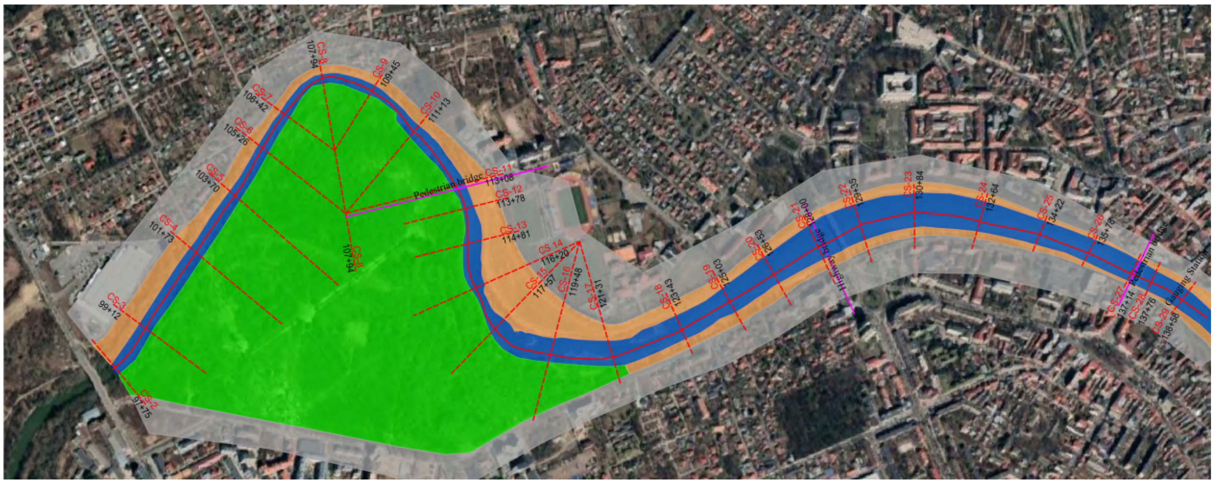

Figure 3. Land cover: blue – water; yellow – flooded vegetation; green – trees; grey – built-up area.

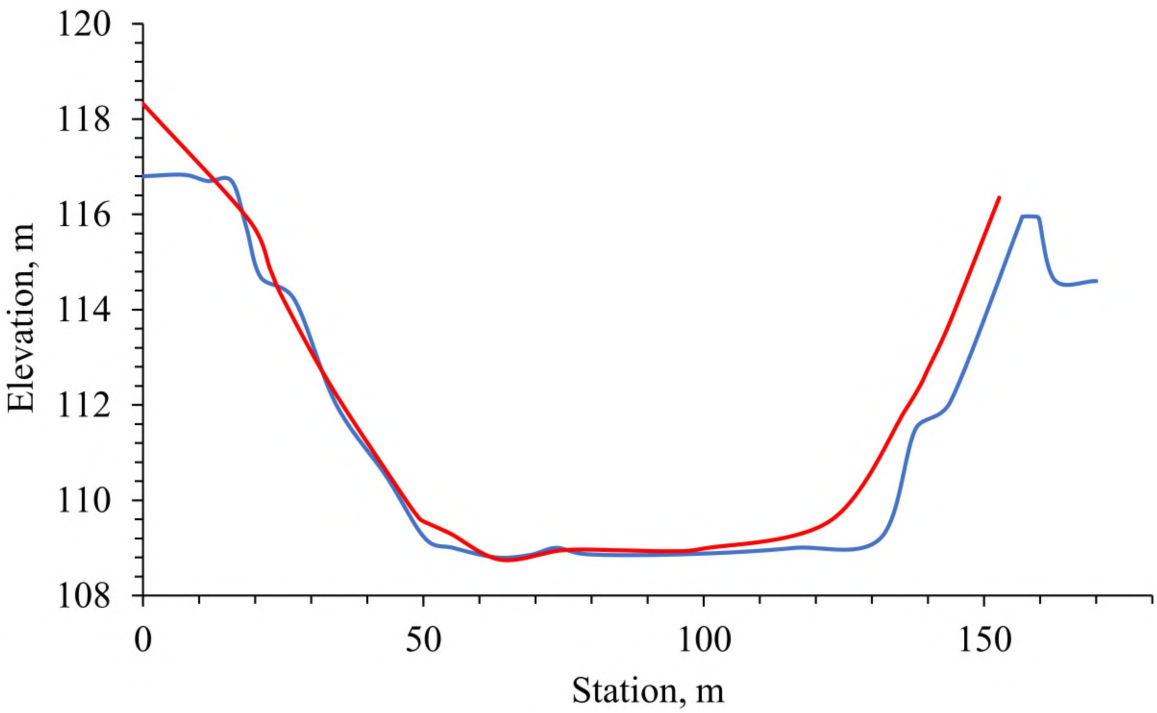

Figure 4. Comparison of cross sections: blue line – topo-geodetic survey; red line – from DEM resolution 30 m.

3. Results and discussion

Flood control measures is carried out for flood flow of 1% probability according to Ukrainian standards for urban areas. Monitoring of water levels and calculation of discharge has been carried out continuously for more than 70 years at the Uzhhorod gauging station. The observations are representative and the flood discharge of 1844 m^3/s was taken for calculation as 1% probability flood flow.

The purpose of calculating using the 1D flow model on the HEC-RAS was to determine the position of the flood surface, to compare the flood level with the embankment elevation and, in case of overflow, propose flood control measures, trying as much as possible not to affect the architectural ensemble of the central part of the city. We used the 1D HEC-RAS modelling because it gives good results in cases of flood propagation along the main river [21] and we didn't have DEM of high resolution to simulate 2D flow accurately. 1D HEC-RAS modelling allows to receive results in the form of a profile with water levels and data in the form of tables for further processing. It is also possible to plot inundation zones, but for data analysis it is more convenient to use a profile for overflow assessment in riverbed limited by dykes.

To assess the reliability of the embankments, we plotted the results of the calculated flood flow of 1% probability, the top of the left and right banks of the river, historical flood in 1992 according to the data of high-water marks on the profile (figure 5). It can be seen from the figure that the flood flow of 1% probability passes free under the bridges, the suspension bridge near the park area has the smallest free room, but it is quite sufficient. The central part of the city from the gauging station to the Babyak's bridge on the right bank of the river are protected by dykes from the overflow of the flood flow. A short site has a slight 15cm decrease and flood risk in front of the Masaryk's bridge from CS-22 to CS-23 on the right bank. The area near CS-17 has a local lowering of the right-bank dyke approximately 70m long, through which an overflow may occur. The left bank of the Uzh River is reliably protected from flooding from the gauging station to the beginning of Bozdos Park CS-16. The left bank with the old dyke is significantly lower on the site below CS-16 to the Babyak's bridge, which is confirmed by periodic flooding of the lower part of the park. The dyke ends above the gauging station on the right bank, so the children's railway and buildings in the Botanic Garden will flood, the privet houses have high concrete retaining wall in this part of the city and will not be flooded.

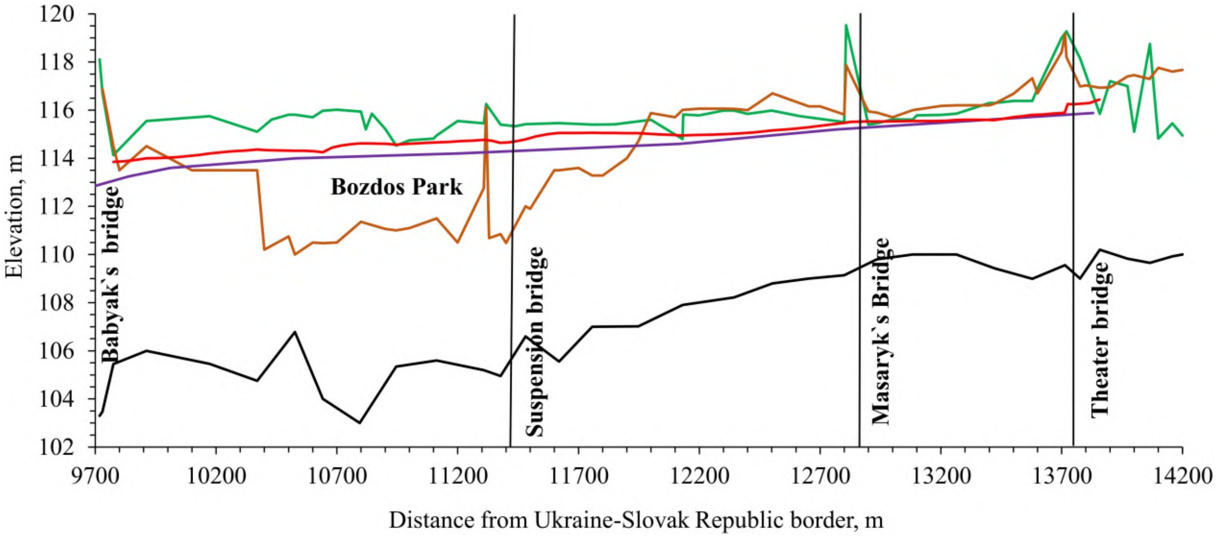

Figure 5. The flood of 1% probability elevation, calculated on the 1D flow model: black line – bottom of the river; green line – right bank; brown line – left bank; violet line – high water marks of the flood in 1992; red line – flood of 1% probability.

The calculation of the extreme flood levels shows that some parts of the central embankment are not sufficiently protected. There are dykes in the city, which generally fulfil their function. Therefore, the flood protection will have combined measures, which include both the "grey" existing system and additional "green" measures that will strengthen the reliability flood control measures. Environmentally friendly measures, as shown by the analysis in the introduction, include retention reservoirs, floodplain expansion, and the use of old river bed.

According to studies [9–11], an effective method of mitigation flood measures is the accumulation of flood runoff in dry mountain reservoirs and polders. The volume of flood flow of 1% probability on the site of the Uzhhorod gauging station is 294 million m^3, the accumulation of even a tenth of the flow requires a reservoir with a significant volume. According to the Program of Flood Protection of the Tisza River Basin, several possible locations for the retention reservoirs construction were proposed in the Uzh River basin (figure 6): 1 – dry retention reservoir of 10.44 million m^3 on the Ulychka river, 2 – dry retention reservoir of 9.3 million m^3 on the Luta river, 3 – polder with volume of 9.44 million m^3 on the Tur'ya river. The retention reservoirs are located at a considerable distance from the city of Uzhhorod, and as study [9] shows, their impact on long distance down will be very insignificant. There are silted lakes on the territory of Bozdos Park, which, after cleaning, can retain a small volume of water, 170,000 m^3.

It is not possible to carry out measures to expand the floodplain within the city limits. The Uzh River floods the Botanic Garden and the children's railway above the gauging station during extreme flood. The construction of dyke will change the landscape, significantly narrow the floodplain and raise water levels in the central part of the city, which is undesirable. At the same time, it is possible to allow the flood flow to spread within the green zones (Botanic Garden, lower part of Bozdos Park), protecting buildings with local mobile barriers. Mobile flood barriers will allow not to narrow the floodplain in green zones and use their retention capacity. The local lowering on short sites along the embankments will be protected by mobile barriers, the foundation of which is located in the underground part of the embankment, and the upper barrier is installed only during the extreme flood, the required number of people to assemble a 100m barrier is 6-8 people, assembly time 1 hour [16].

The old river bed of the Uzh River is located on the territory of the Bozdos Park (figure 6), which, after clearing and strengthening, can be used to discharge part of the runoff and lower the flood levels in front of the suspension bridge.

Figure 6. Flood mitigation measures: 1, 2 – dry retention reservoirs; 3 – polder; 4 – dyke 1% probability; 5 – dyke 10% probability; 6 – old river bed; 7 – oxbow lake; 8 – mobile barrier; 9 – retaining wall; 10 – mobile protection of single building.

4. Conclusions

1. Calculations of the flood level of 1% probability using the 1D HEC-RAS model showed that the central part of the city is protected from flooding by the existing dykes, except for few areas that can be protected by local mobile barriers.
2. It is not possible to create "green" flood infrastructure in the existing city. But we can try to achieve a holistic approach, trying as much as possible to use environmentally friendly measures approaching the concept of sustainable city.

3. Since the backwater by flap gates is planned near the suspension bridge and Bozdos Park, it is necessary to carry out a more accurate 2D modelling of the combined operation of the river, old river bed and oxbow lake during the extreme flood to assess the impact of the structures on the flood levels.

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Physical and mechanical properties of burnt-out coal mine waste heaps

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Physical and mechanical properties of burnt-out coal mine waste heaps

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Abstract. Currently, the issue of finding new ways to process, utilize and reuse burnt-out waste heaps in order to reduce their technogenic impact on the environment becomes relevant. The presence of a porous structure in combination with undissolved properties opens up the possibility of using the burnt-out mine rock to make composite fertilizers to improve the quality of agricultural and technogenically degraded soils. The widespread use of burnt-out mine rock for the manufacture of composite soils requires the study of their physical and chemical properties and deformation characteristics. In laboratory conditions, the physical and mechanical properties of samples of burnt-out rock masses ranging in size from 1.25 to 10 mm with and without the addition of powdered soil under a load of up to 110 kN were studied. For the first time, a certain increase in load resistance was found when soil powder was added in the initial period of compression of the tested material. It was determined that the destruction of particles of burnt-out material occurs in two waves. These results indicate the presence of two strength limits in the burnt-out medium composed of two initial petrotypes.

1. Introduction

The coal industry of Ukraine is one of the most important branches of the mining industry, since it is the main supplier of raw materials for domestic power and metallurgical enterprises, as well as an exporter of extracted products to world markets [1]. Despite the trend towards popularization of alternative energy sources, it is expected that the intensity of coal mining will increase annually due to the demand for energy raw materials in the world [2], which is associated with the energy crisis, rapid industrialization, and population growth [3].

Underground coal mining causes various environmental problems that cause significant damage to the environment and natural biocenoses. These problems include exogenous and endogenous fires [4], methane emissions [5], water pollution by mine wastewater, surface subsidence, destruction of biodiversity [6], and soil degradation [7]. A special part is played by the problem of solid mining waste management, which often contains substances that are harmful and hazardous for the environment [8], and their deposition contributes to dust and toxic gas emissions, as well as toxic solution washing-off.

The practice of coal mining enterprises has shown that one ton of coal produces about 0.4-0.5 tons of waste rock. This figure is an average and may vary depending on the quality and strength of the coal seam. Thus, for coal basins in Ukraine, this figure is in the range of 0.12-0.39 tons, and 0.4-0.5 tons in Poland [9].

Modern mining technologies used in different coal-producing countries are mainly aimed at the fullest possible extraction of coal from the longwall [10] and accumulation of waste rock in the mine working space without recovering it to the surface [11]. This method minimizes the amount of solid waste generated during coal mining and reduces the technogenic impact on the environment. However, just like 20-40 years ago, most coal mines in Ukraine continue to operate according to the old scheme: the bulk of the waste rock is not utilized but is placed near coal mines, forming waste heaps of various configurations. This has led to the accumulation of more than 25 billion tons of solid mining waste in the country's coal mining regions [12], which is stored in more than 1,000 waste heaps [13].

Waste heaps cause significant environmental damage. Being under the constant influence of climatic factors, their surface is subject to wind and water erosion, as a result of which dust, as well as oxidized compounds of sulphur, iron, carbon and other harmful elements, enter water bodies [14] and adjacent agricultural soils, thereby contaminating them [15].

However, the greatest danger of waste heaps is their fire and explosion hazard. This is especially true for old heaps. This is due to the fact that chemical and biological processes in the waste mass, involving pyrite and coal, have been occurring for many years with the release of elevated temperatures and are often accompanied by smouldering, burning [16], and sometimes explosions [17]. Such fires are a source of dust and gaseous substances emitted into the atmosphere, and the high temperatures [18] accompanying the fires pose a threat to the population within the radius of the waste heaps [19]. Therefore, the issue of finding new ways to process, utilize and reuse burnt-out waste heaps in order to reduce their technogenic impact on the environment becomes relevant.

2. Literature review

Waste heaps in the coal basins of Ukraine mostly consist of a coarse mixture of mudstones, siltstones, sandstones, pyritized and other types of rocks with a number of components, such as aluminium, zinc, sulphur, titanium, molybdenum, which is why they can be considered as valuable secondary deposits. The direction of possible reuse of waste heaps is determined by the physical and chemical characteristics of the waste mass. However, during prolonged burning, under the influence of high temperatures ($1000...1200\,^{\circ}C$), changes occur in the structural characteristics of the original rock, which leads to the formation of new material from the waste mass of varying degrees of burning-out: from sintered to slightly burnt, with different strength, water permeability and porosity. These indicators should be taken into account when determining promising areas for further use of burnt-out mine rock.

Burnt-out waste from coal enterprises has great potential for use in the construction sector [20]. Thus, studies have shown the prospects of using burnt-out mass for the manufacture of porcelain stoneware [21], cement mixtures, modified building insulation materials, and materials for backfilling mine workings [22].

It is recommended to use burnt-out mine rock in a concentration of 50% for the manufacture of modified foundations. Due to the use of modified material from burnt-out solid waste, which has stable characteristics, the bearing capacity and strength of foundations constructed on loess soils increases [23]. For buildings constructed in areas that are prone to surface subsidence, such as over mine shafts, it is recommended to use a three-layer slab foundation, in which one layer is made using burnt-out rock. In this case, the use of burnt-out waste rock will not only increase the reliability of buildings but also improve the environmental situation in the coal mining region.

Given the shortage of local natural stone raw materials, the use of burnt-out waste heaps in coal mining regions for the construction of structural layers in the construction of pavement is of particular relevance [24], or for the creation of subgrade in the levelling of sites [25]. This minimizes the costs associated with the extraction and transportation of stone raw materials.

The presence of a porous structure in combination with undissolved properties opens up the possibility of using both burnt-out and common mine rock to make composite fertilizers to improve the quality of agricultural and technogenically degraded soils. To do this, the rock is mixed with an organic component, which can be municipal sewage sludge or water body silt. Studies have shown that the addition of coal industry waste and its mixtures with municipal sewage sludge and rock wool waste improves soil pH and its occlusion properties [26]. Laboratory studies have confirmed that the creation of a nutrient mixture based on 25% burnt-out mine rock, 25% river silt, and 50% degraded loamy black soil treated with red California worms allows for 100% germination of tomatoes, unlike other substrates that did not contain burnt-out rock [27].

However, the widespread use of burnt-out mine rock for the manufacture of composite soils requires the study of their physical and chemical properties and deformation characteristics.

The purpose of this paper is to evaluate the effect of particle size distribution on the physical and mechanical properties of burnt-out waste rock.

3. Research methods

The study of the physical and mechanical properties of experimental samples of burnt-out rock mass was based on DSTU BV.2.1-4-96 "Soils. Methods of laboratory determination of strength and deformation characteristics" [28].

The process of deformation of the mixture of burnt-out waste mass and soil was studied. Samples for the study of rock properties were taken from the non-operational heap of mine No. 5/6 of the Myrnohradvuhillya Production Association (Myrnohrad). The rock was sampled at five points from a depth of up to 10 cm using the "envelope" method. The sampling site had no signs of intense oxidation, burnt zones, etc. The initial waste mass was represented by interspersed layers of siltstones and mudstones (sand shales) with sandstones. In the burnt-out state, their residues were: dark – siltstones, light grey – mudstones and sandstones. The gradual burning-out of rocks occurred slowly over several decades under the influence of atmospheric processes: oxygen, moisture, wind, bacteria, temperature changes, etc. The largest of the selected pieces were crushed mechanically. After crushing the rock, the resulting particles were separated using laboratory sieves into fractions, *mm*: 10...5; 5...3; 3...1.25. Preliminary laboratory studies have shown that the burnt-out mine rock of larger fractions have characteristics which not suitable manufacture of composite soils. Therefore, physical and chemical properties and deformation characteristics was carried out only for fractions 10...5; 5...3; 3...1.25.

Each rock fraction was microscopically examined using a monocular microscope XSP – 128 and a camera Levenhuk M1000 PLUS. The magnification of the images was the same. To compare the geometric dimensions of the inclusions and the parameters of irregularities and pores, a 0.02 *mm* Momoi Hameleon Extreme fishing line was included in the image composition as a geometric reference.

For both petrotypes, namely dark and light, the particle shape, the nature of its edges, the presence of visual porosity, cracks and faults were assessed for each fraction.

To determine the deformation characteristics of the rock in each fraction, 4 samples were prepared: a reference, without additives, and three samples each with the addition of loamy soil typical for the area with mass concentrations of 10, 20, and 30 percent. The soil additives in powder form were thoroughly mixed with the dried rock. The weight m (g) of the samples and their bulk density ρ_{pb} (g/cm^3) were determined by the weight method (table 1). The table shows that the addition of soil powder led to an increase in the density of the mixture compared to the 'pure' (0 percent additive) rock by 0.03...0.15 (g/cm^3). However, the difference in this indicator, when adding 10...30 percent (wt.) of soil, was within the measurement error.

Table 1. Data of laboratory studies for determining the bulk density and weight of the studied samples of burnt-out mine rock.

Percentage of soil in the mixture, %	Fraction size, *mm*					
	5...10		3...5		1.25...3	
	$m,\ g$	$\rho_{pb}, g/cm^3$	$m,\ g$	$\rho_{pb}, g/cm^3$	$m,\ g$	$\rho_{pb}, g/cm^3$
0	290	1.08	281	1.04	301	1.12
10	300	1.11	320	1.19	326	1.21
20	300	1.11	320	1.19	326	1.21
30	300	1.11	320	1.19	320	1.19

The prepared samples were placed in a steel cylinder (figure 1) with a diameter of *d=7.5 cm* and a height of *h=6.1 cm*. The steel cylinder with samples of burnt-out mine rock was covered with a massive metal plunger and placed between parallel press plates and subjected to loading.

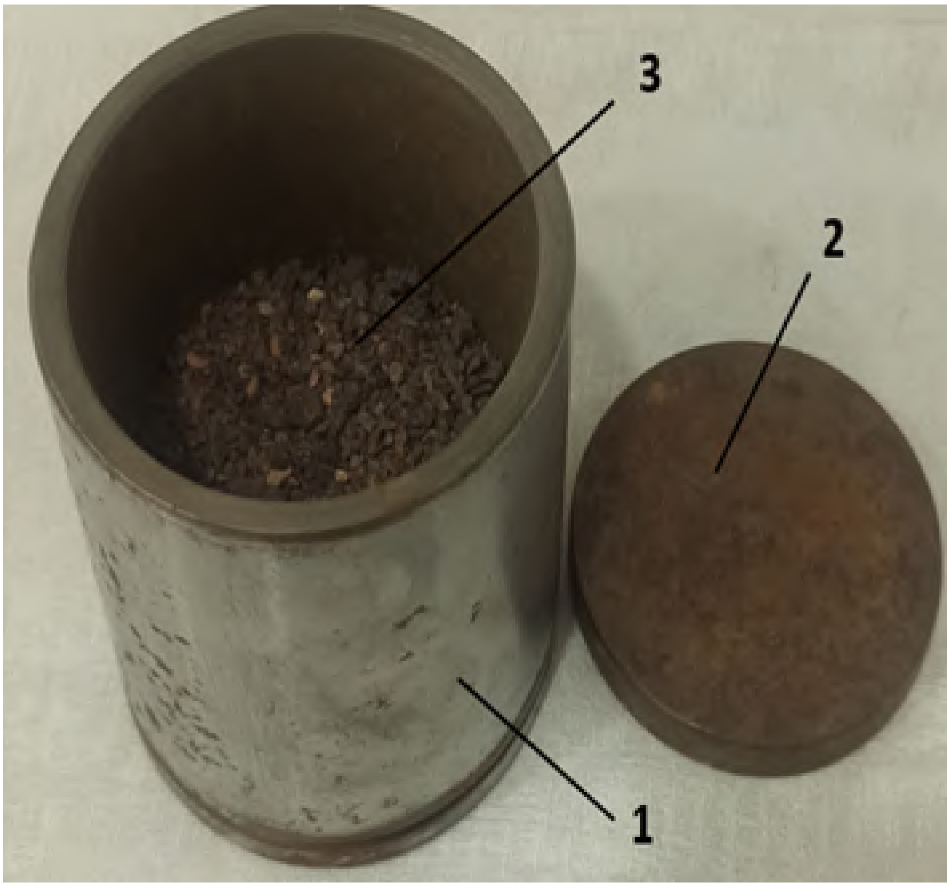

Figure 1. Device for experimental determination of deformation characteristics of burnt-out mine rock: 1 – steel cylinder, 2 – plunger, 3 – experiment sample.

The deformation characteristics were determined using a press P-50 (figure 2, *a*). The loading speed was automatically adjusted to 0.21 *m/s*, and the loading force of the samples was increased

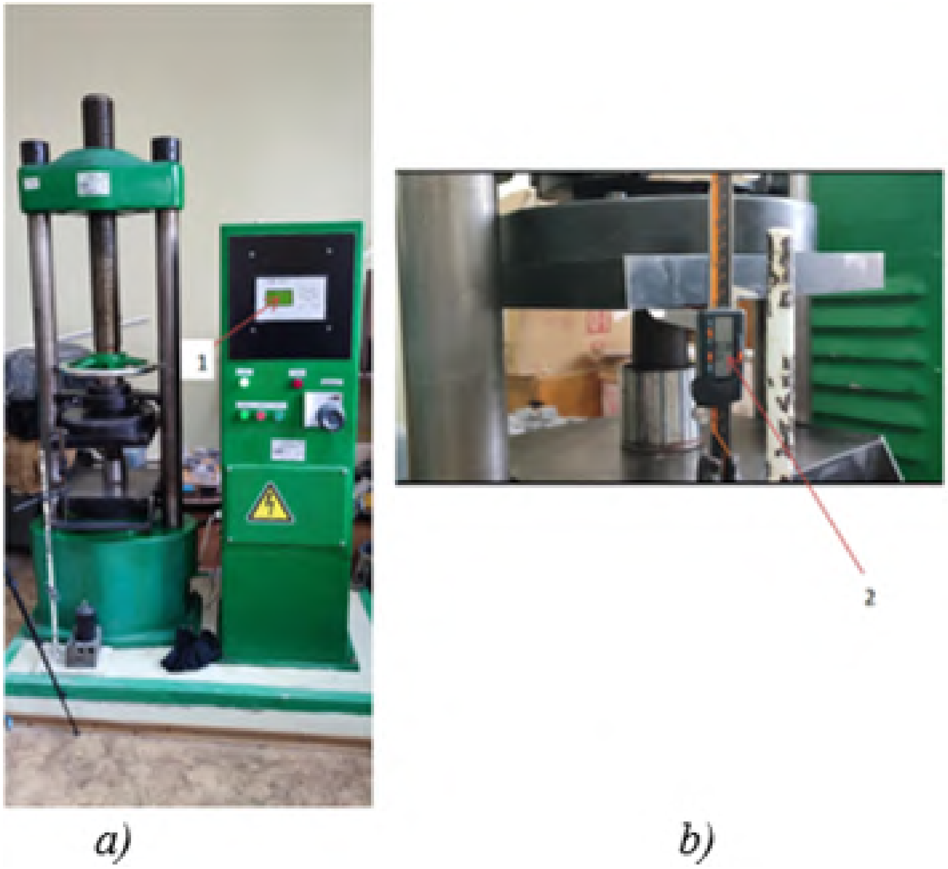

Figure 2. Laboratory setup for measuring the deformation properties of soils: *a)* – general view of the P-50 hydraulic press, 1 – indication of the compression force, F, N; *b)* – strain measurement unit, 2 – indication of plate convergence Δh, m.

from 0 to 110 kN. At the same time, the convergence of the press plates was recorded (figure 2, b), which corresponded to the deformation of the sample. The experiment was timed using a laboratory stopwatch.

The task of the observations was to record the dynamics of changes in the height of the sample Δh, m, which corresponded to the action of a certain value of the compressive force F, kN.

The test results were processed using the following formulas. Relative vertical deformation of the sample ε:

$$\varepsilon = \frac{\triangle h}{h} \tag{1}$$

where Δh is the value of the vertical absolute deformation of the sample under load, m; h is the initial height of the sample, m.

Energy E, J, which was spent on compressing the sample to a value of Δh:

$$E = F \cdot \Delta h, J, \tag{2}$$

where F is the sample compression force, N.

Pressure in the rock sample P, Pa:

$$P = \frac{F}{S}, Pa, \tag{3}$$

where S is the cross-sectional area of the cylinder, m^2.

Power W, W, of compression of the sample:

$$W = \frac{E}{t}, W, \tag{4}$$

where t is the duration of the loading process, s.

4. Research results

The results of microscopic examination of particles of different fractions are shown in figure 3 and table 2.

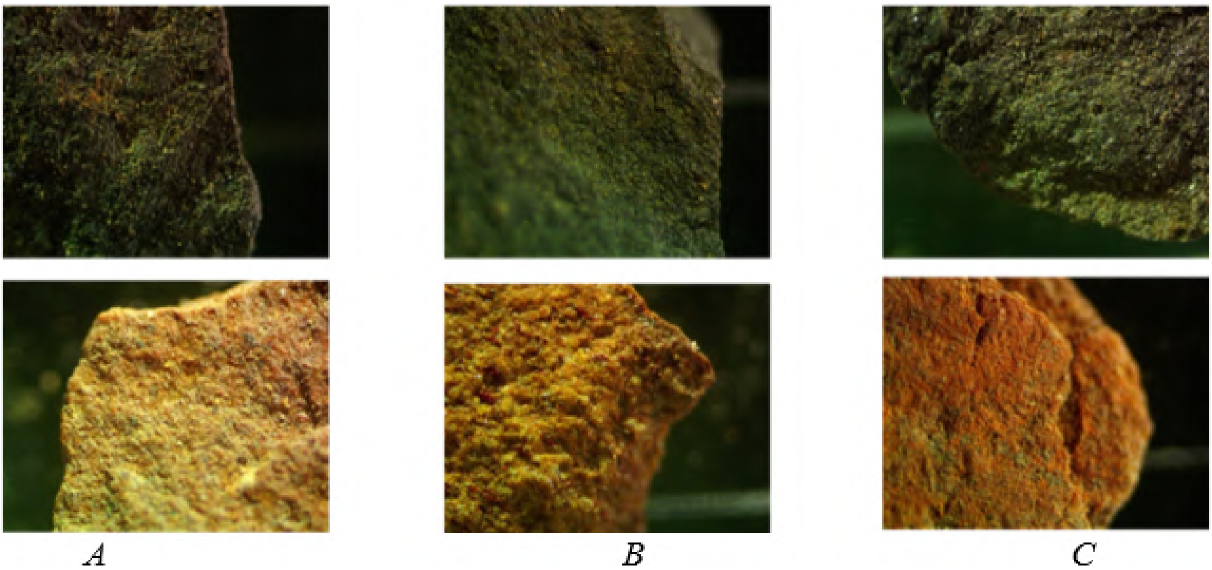

Figure 3. Microscopic images of rock samples, dark: mudstones, light: siltstones and sandstones: A, B, C – respectively, fractions (mm), 10...5, 5...3, 3...1.25.

The particles of the 10...5 mm fraction (figure 3, A) of the rock have a pronounced flat shape with a diverse geometric structure. The edges of the particles are rounded with uneven protrusions. The surface is porous with a small number of depressions, there is a significant number of inclusions of yellow colour, a smaller amount of orange and black; no cracks are observed. The relatively uniform nature of the surfaces indicates a low probability of air bubbles accumulation on them, and air retention is possible mainly in the space between rock particles.

The rock particles of the 5...3 mm fraction (figure 3, B) have both flat and three-dimensional shapes, resembling pyramids and parallelepipeds. The edges of the particles have the shape of sharp angles, and the protrusions of inclusions are pronounced. The porosity of the rock surface is increased, there is a large number of mineral inclusions of yellow, orange and white colour; no cracks are observed. The light-coloured particles are characterized by a pore-like texture, which may contribute to the retention of air bubbles covered with suspension.

The particles of the 3...1.5 mm fraction (figure 3, C) have three-dimensional shapes, the vast majority resembling grains and pyramids. The edges of the particles are rounded with faults, and inclusion protrusions are pronounced. The porosity of the rock surface is increased. A large number of inclusions: yellow, orange, white, black and transparent. Cracks and faults are observed on both dark and light-coloured particles, which can serve as air collectors.

Table 2. Characteristics of the fractions of the studied samples of burnt-out mudstones and siltstones.

Particle characteristics	Fraction, *mm*					
	10...5		5...3		3...1.5	
Initial rock	mudstone	siltstone	mudstone	siltstone	mudstone	siltstone
Shape	flat		flat and three-dimensional		three-dimensional	
Shape edge	rounded	sharp corners	pronounced sharp corners		rounded	
Porosity	porous	porous	increased porosity		increased porosity	
Cracks	–	–	–	–	+	+
Faults	+	–	–	+	+	+
Inclusions of a certain colour*, %						
Yellow	22	38	18	42	28	34
Orange	2	5	–	16	5	8
White	–	–	6	8	4	9
Black	–	11	–	–	–	8
Transparent	11	–	10	–	9	18

* Inclusions are calculated in % of the total area of the studied rock surface of a certain fraction.

From the results presented in table 2, it follows that particles with a size of 10 to 3 *mm* are characterized by a flat (scaly) shape, they are porous, there are no cracks, and there are stepwise faults.

Smaller particles are characterized by a rounded shape, greater porosity, and a higher frequency of cracks and faults. Unlike others, the 5...3 *mm* fraction is characterized by sharp edges, which may affect the nature of the deformation process. In the larger fraction, the presence of sharp protrusions is less pronounced.

According to the results of force tests, it was found that there is a parabolic relationship between the energy expended on the compression of the rock sample and its deformation (figure 4). It is valid for all types of the tested samples. At the beginning of loading, deformation occurs at a high rate. Thus, 50 J was sufficient to achieve a vertical deformation of Δh= (0.014...0.018) m. However, at a level of more than 50 J, a sharp increase in the energy required to reduce the height of the sample is observed. At a load in the range from 50 to 250 J, the level of additional deformation was only about Δh=0.01 m.

The addition of soil to the fraction of 1.25...3 *mm* in the amount of 10% did not significantly affect the deformation pattern of the sample (figure 4, A), which did not differ from the deformation of pure rock. An increase in the soil additive to 20...30% led to an increase in the value of Δh by about 0.005 m at the initial stage, with a load of up to 50 J. With further loading, the deformation dynamics was the same for all samples.

All samples of the 3...5 *mm* fraction were compressed in a single movement (figure 4, B) as a whole. A similar pattern is also characteristic of samples of 0, 10, 20% of the 5...10 *mm* fraction (figure 4, C). At the initial period of loading (up to 50 J), a close to Δh=0.002 m increase in deformation is inherent in the sample with the addition of 30% soil.

For almost all tested samples, the final deformation was about Δh=0.02...0.025 m at a loading energy of 250 J. The exceptions were samples of 0 and 10% of the 1.25...3 *mm* fraction, where this indicator was Δh=0.016...0.018 m (figure 4, A).

It should be noted that the 'power-deformation' diagrams reflect the reaction of the samples to the force impact of the loading setup. Of interest are the dependencies between the load and the power spent at this pressure in the test material. Such dependencies show the dynamics of deformation of the dispersed medium under uniaxial vertical loading with a horizontal

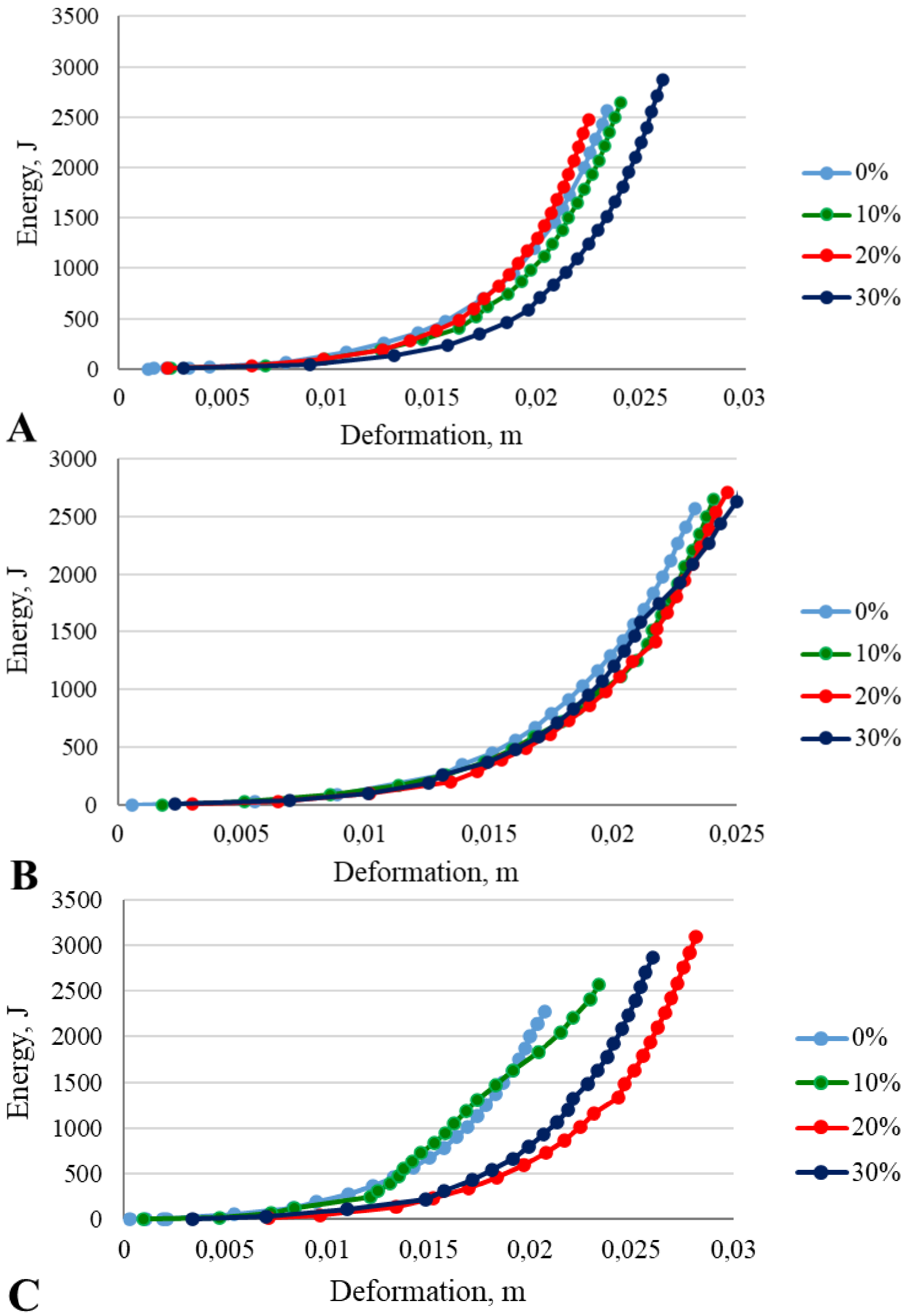

Figure 4. Energy (J) spent on deformation (Δh, m) of the samples: A, B, C – respectively, fractions (mm), 1.25-3; 3-5; 5-10.

displacement limit. The results of the study in the form of 'power-pressure' diagrams are shown in figure 5. The results obtained are visually strikingly different from those shown above. There are no smooth lines, and their synchronous location. The graphs illustrating the dependence of the power required to compress the sample are characterized by a broken form, and in many cases, there are extremes. It is known that line bends, and especially the presence of extreme points, indicate a qualitative change in the nature of the process under study.

It can be assumed that the change in the deformation mode of the sample is caused by the accumulation of potential energy in the rock particles and the mutual sliding of the particles of the discrete medium, as well as the transition of the potential energy accumulated in the particles to kinetic energy by breaking the particles and subsequent movement. Particle breaking can occur by separating sharp edges, separating rounded particles, etc. Due to the chaotic arrangement of particles in the steel cylinder (figure 1), individual elements of the process of rock particle movement and breaking are not clearly reflected in the graphs, but when a common phenomenon characteristic of the sample scale occurs, it manifests itself in the form of bends or extremes.

The analysis of the results of loading rock samples without the addition of soil powder is indicative. The power increase in the largest (5...10 mm) fraction (figure 5, A, item 1) was observed linearly with an approximately uniform rate up to the level of 7 W and a pressure of about 3800 kPa, after which the power increase rate decreased until the end of the experiment (W=9 W, P=5800 kPa). It can be assumed that at the initial stage, the energy of rock particles was accumulated, accompanied by simultaneous particle breaking and the appearance of small particles. Subsequently, after reaching a high pressure level comparable to the tensile strength of the material, the process of breaking with particle movement has intensified, but the required power increase has decreased.

It should be noted that the absence of powder provided a high level of contact stresses between the particles, which contributed to their intensive breaking. This is indirectly confirmed by the test graphs of samples of 5...10 mm fraction with the addition of powder; all lines (figure 5, A, items 2, 3, 4) are above the line of pure rock. In the samples with the addition of soil, due to the increase in the contact areas of energy accumulation, an intensive increase in power occurred at the initial stage without significant crushing and sliding of particles.

When loading the samples of clean rock of 3...5 mm fraction (figure 5, B, item 1), an intensive power increase occurred to a level of about 7 W and a pressure of up to 1800 kPa, after which there was a slight decrease to 6 W at 2000 kPa. It should be noted that the number and area of contacts between the particles in this fraction is much smaller than in the previous one, so the difference between the pure rock and the one with additives is not so significant. This indicates that up to a certain level of load, the particle crushing was of a small scale, and after reaching a certain limit, breaking and sliding occurred. The power level of such a limit was 6...8 W, i.e., close to that when loading a larger fraction at 1500...2000 kPa (figure 5, B, items 1, 3).

The deformation pattern of the sample of the 1.25...3 mm fraction was close to that of the coarse fraction, the graph curve (figure 5, C, item 1) is similar to (figure 5, A, item 1), only the bend point had the coordinates W=10 W, P=4000 kPa, which can be explained by a larger number of contacts between small particles and, therefore, a lower level of contact stresses at the same pressure level.

The presence of powder in the mixtures reduced the destructive role of contact stresses, which sometimes required higher power levels for loading at relatively low stresses (figure 5, A, item 3, figure 5, B, item 2, figure 5, C, item 4).

In the process of loading, more than half of the samples of the three fractions showed a rapid increase in pressure to a level of about P=1500...1800 kPa and power to W=7...11 W, followed by an increase in pressure to P=2000...2200 kPa accompanied by a decrease in power level by 2...3 W, sometimes more. Subsequently, the increase in power and pressure occurred at

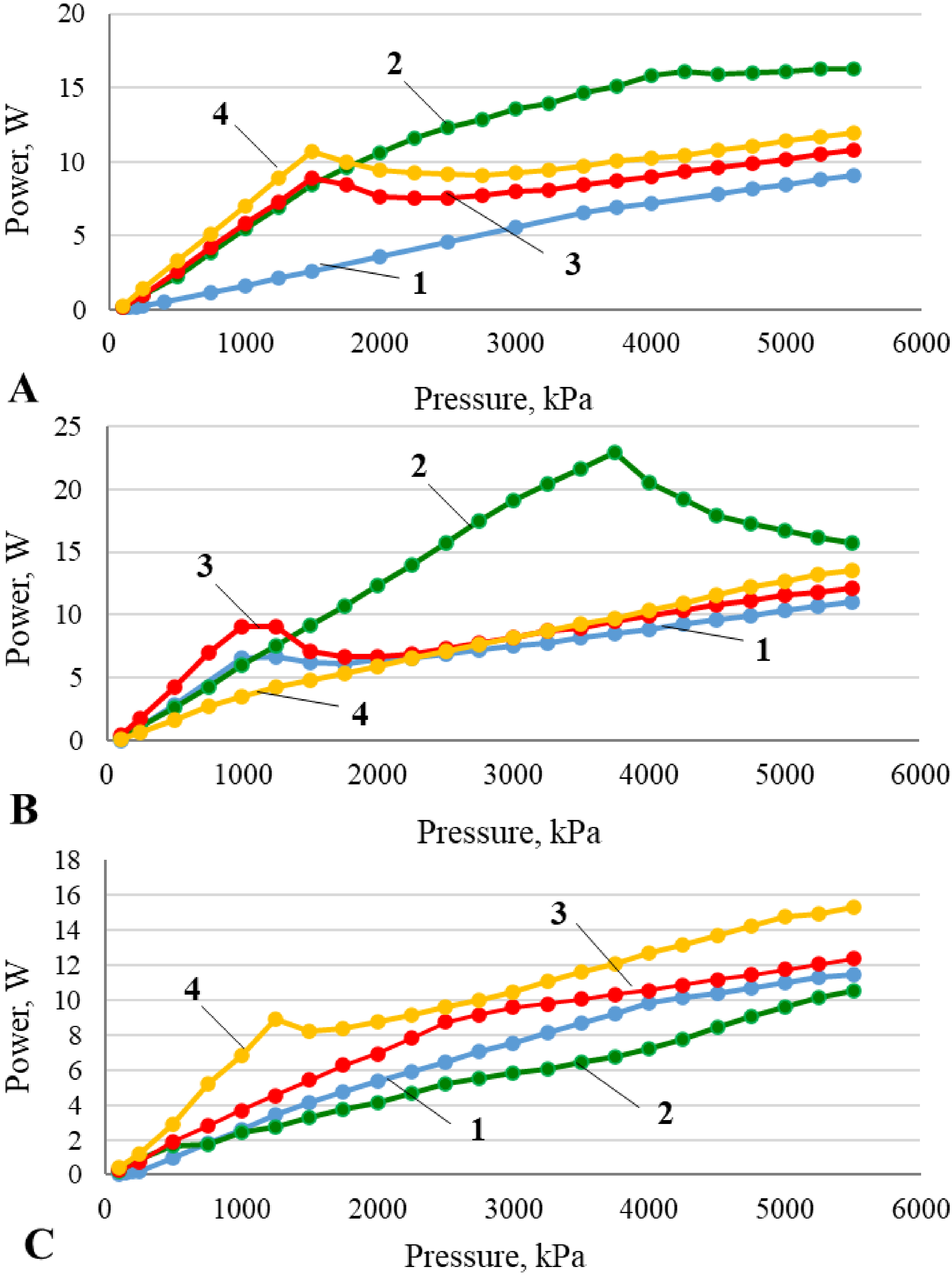

Figure 5. Power W (W) consumed to compress rocks to a pressure P (kPa): rock without additives; 2,3,4 – respectively, 10, 20, 30% of soil powder added: A, B, C – respectively, fractions (mm), 5-10; 3-5; 1.25-3.

a constant rate for all samples.

The reference rock samples of each fraction, after loading up to 110 *kN*, were sieved and the percentage of rock that was crushed was determined (table 3). These data showed that a significant portion of the energy used to compress the rocks was spent on crushing the rock particles, and the rest on compacting the sample. The largest percentage of crushing is inherent in the larger fraction. Particle breaking occurs at the points of contact with neighbouring particles, when the level of contact stress exceeds the tensile strength. Such conditions are more likely to occur when larger particles interact due to a smaller number of contacts and a corresponding increase in contact forces. Such processes can be manifested in the form of an abrupt change in the Δh indicator. Moreover, the deformation of small fractions should be almost twice as smooth as that of large ones.

Table 3. Percentage of rock crushed after loading of the reference samples.

Fraction size, *mm*	Fraction weight, *g*		Proportion of crushed rocks, %
	before	after	
5-10	290	96.76	66.63
3-5	281	174.04	38.06
1.25-3	301	209.31	30.46

5. Discussion of the results

The study of the deformation properties of mixtures of rocks and powdered additives is necessary, e.g., for the construction of road bases using burnt-out rocks. The addition of a sufficient amount of powders that swell under the influence of water, such as montmorillonite, to gravel or crushed stone allows for creating a waterproofing 'jacket' that prevents water from penetrating the road body and deforming it during freezing and thawing. The availability of deformation data sheets for the mixture allows for establishing a consensus between the bearing capacity of the mixture and its waterproofing properties.

The results obtained revealed a certain increase in load resistance when soil powder was added during the initial compression period (figure 5). Almost all the lines of the graphs characterizing the power required for compression located above the line are characteristic of pure (0% soil additive) rock. This can be explained by the contact stress levelling effect due to the filling of voids with powder and, therefore, an increase in the interaction areas of rock particles. The destruction of rock particles was observed, in most cases, at a pressure of 1500...1800 *kPa*, which is typical for burnt-out mudstones. After crushing such particles, their mutual sliding occurred with a slight decrease in the power required for further deformation. The next wave of particle crushing was observed when the pressure increased to an index approximately equal to 3800...4000 *kPa* (figure 5, *A*, items 1, 3; figure 5, *B*, item 2; figure 5, *C*, items 1 and 3), which is typical for siltstones and sandstones. Subsequently, the rate of pressure growth slowed down. After the active destruction of rock particles was completed, the material consolidated and deformation of the samples occurred at almost the same rate. These results indicate the presence of two strength limits in the burnt-out medium composed of two initial petrotypes.

The methodology of the experiment did not provide for the registration of the process of rock breaking, only its results were reported (table 3). In the future, it would be advisable to observe mechanical and acoustic phenomena in the samples in parallel with the compression of the samples to clarify the periods of intense rock destruction. An additional disadvantage of the conducted research should be considered the limited scope of the experiments both in terms of the number of samples and the number of experimental objects, only one waste heap was considered. This can be explained by the difficulty of working under martial law, and the shortcomings will be eliminated in the future.

Microscopic studies have shown the presence of various types of mineral components that make up burnt-out rocks. The photographs (figure 3) clearly distinguish inclusions of yellow, orange, white, black, and transparent colours (table 2). No mineral analysis of these inclusions was performed. However, based on the literature data, it is possible to provide a rough estimate that red and orange inclusions are typical for iron oxides, yellow – for sulphur compounds, white and transparent are quartzite, black are carbon compounds. This approach is very approximate and should be further refined. However, different types of minerals have different attitudes towards water, namely, they can be hydrophilic or hydrophobic. This is an important characteristic of the material in its practical use, so was evaluated the occlusion capacity of the burnt-out waste rocks of mine No. 5/6 [29]. Laboratory studies have shown that burnt-out rocks are able to retain a certain amount of liquid on their surface, the so-called film water (W_f), as well as capillary water, which is retained in pores and cracks (W_C). The latter indicator was defined as an increase in the moisture capacity of the rock (W_{RC}=W_f+W_C) after prolonged (up to 24 hours) saturation with water that penetrated into cracks and capillaries in the rock particles (table 4).

Table 4. Fractional indicators of the capacity of film occluded and capillary water in burnt-out rocks.

Fraction, *mm*	W_{RC},%	W_f, %	W_f/W_{RC}, particle
5-10	8.08	6.96	0.86
3-5	12.58	11.36	0.90
1.25-3	13.60	12.96	0.95

The total moisture capacity W_{RC} increased from 8.08 to 13.6% relative to the mass of dry rock with decreasing fraction size. The occluding surface of larger particles (5-10 *mm*) was the smallest with the same weight of the experimental samples, so the film water indicator was the lowest. Experimentally, it was found that for a geometrically smaller fraction (1.25-3 *mm*), which is three to four times smaller, the W_{RC} indicator was about 40% higher.

The data obtained are also needed in the future to reveal the mechanism of deformation of a mixture of rocks with wet bottom sediments [30]. The thing is that in addition to solid and liquid components that are almost incompressible, the mixture may contain air. It is an elastic substance and affects the results of the experiment. When wet materials placed in a test vessel are loaded, the gases are not completely displaced, but migrate to pores, cracks, etc. When testing dry samples, this phenomenon is not observed, instead, moisture isolates the gaps between the particles and seals air bubbles, which change their volume during loading and unloading, which affects the deformation of the material. The test methodology does not provide for control of the presence of air in the test medium.

To assess the impact on the deformation of a mixture of rock and wet sediments, it is necessary to consider the possibility of air in the pores, cracks, and gaps between the particles. Visual observations and research show that in the process of burning-out, the waste masses become close in properties to ceramics; their particles do not increase in volume when wet.

6. Conclusions

In laboratory conditions, the physical and mechanical properties of samples of burnt-out rock masses ranging in size from 1.25 to 10 *mm* with and without the addition of powdered soil under a load of up to 110 *kN* were studied. For the first time, a certain increase in load resistance was found when soil powder was added in the initial period of compression of the tested material.

It was determined that the destruction of particles of burnt-out material occurs in two waves. The first wave was observed at a pressure of 1500...1800 kPa, followed by material sliding with a slight decrease in the power required for further deformation. The second wave was observed at a pressure increase of approximately 3800...4000 kPa.

It was also determined that after the active destruction of rock particles was completed, the material consolidation and deformation of the samples occurred at almost the same rate. These results indicate the presence of two strength limits in the burnt-out medium composed of two initial petrotypes.

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Stakeholders' awareness and perception of bio-economic transformation in Ukraine

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Stakeholders' awareness and perception of bio-economic transformation in Ukraine

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Abstract. Existing bio-economic strategies are complex political documents that affect all spheres of human life, nature, and the economy and require broad social perception. Despite Ukraine's high bio-economic potential, this term has yet to enter the everyday lives of both politicians and ordinary citizens. The vision of what positive or negative consequences this concept generates and what conflicts and political demands may be associated with it has yet to be accurately formed. The article explores the micro-level perception of bio-economic transformation by critical stakeholders to support policy and strategy development at all decision-making levels. We used quantitative data from surveys in three target groups of respondents (scientific and innovation sector, business and industry, government and non-government organizations) to form an approximate picture of the bio-economic transformation perception from scientific, public, and business perspectives. According to the results, bio-energy and agriculture are considered the sectors of the bio-economy with the highest potential for growth in Ukraine. Respondents of all target groups are united in the understanding that the state bears greater responsibility for communicating and promoting the bio-economy among a broader audience, which is not sufficiently informed about potential advantages and problematic issues. The advantages of bio-economic transformation for the environment are perceived as undeniable. Potential risks are minimized or not perceived as such. The understanding of the role of bio-economic transformation in economic growth, job creation, innovation development, and digitalization is less visible. Almost 20 percent of respondents believe that the problem of insufficient biomass for bio-economic transformation is the most critical risk. Biomass as a raw material of sufficient quality may have other options for creating products with high added value before being used in bioenergy at the end of its life cycle. The risks of insufficient biomass can be partially reduced due to the widespread implementation of the cascade use of biomass and the principles of the circularity of the bio-economy. Thus, it is vital to include circularity, cascading use of biomass, and aspects of the rational resources used in the communication policy of bio-economic transformation, as well as its synergy with the main bio-economic sectors regarding the use of biomaterials and innovative knowledge and technologies with their undeniable positive impact on mitigation climate change. The results of the bio-economy perception survey can be used by stakeholders when developing or revising communication strategies and plans and fill a scientific gap in the perception of bio-economic transformation by various stakeholders in Ukraine.

1. Introduction

There are many definitions of the bio-economy. According to the definition of the European Commission from 2018, "Bio-economy covers all sectors and systems that consist of biological resources (animals, plants, microorganisms and derived biomass, including organic waste), their functions and principles. It includes and interconnects terrestrial and marine ecosystems

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and the services they provide; all primary industries that want and the sector produces biological resources (agriculture, forestry, fishing, and aquaculture); and all economic and industrial sectors that require biological resources and processes to produce food, feed, bio-products, energy, and services. For the successful implementation of the bio-economic strategy, the European bio-economy is based on the principles of sustainability and circularity. According to the European Commission, it will help renew our industries, modernize our primary production systems, protect the environment, and enhance biodiversity" [1]. In this understanding of the concept of bio-economy, we conducted research. The method of bio-economic transformation of socio-economic systems is the transition to an innovative economy with low CO2 emissions, anticipation of development requirements for sustainable agricultural production and fishing, ensuring food security and sustainable use of regenerated biological resources for industrial purposes while ensuring the preservation of biodiversity and environmental protection environment. Traditionally, the bio-economy sector includes agriculture and forestry, fishing, and the food industry, along with traditional industries related to the use of biomass, such as the paper and pulp industry, as well as part of the chemical, biotechnology, and energy industries [2]. To date, more than 40 countries of the world have included the bio-economic concept in the agenda of sustainable development, which is underlined in EC report [3], and indicates the global trends of the transition to a sustainable bio-economy [4]. As one of the largest agricultural countries of the European continent, Ukraine has a high potential for bio-economic transformation. This becomes an even more urgent issue in the context of the risks that the country faces in the war for its raw resources against the Russian Federation, since military actions are taking place in the most mineral-rich territories. The agro-industrial complex remains the main resource for the further development of the country's economy in the near future, and its innovative and sustainable development should become a priority.

At the beginning of its emergence, the term bio-economy was primarily used by scientists who studied the industrial application of evolutionary biology processes. Still, over time it became mainstream in the EU, due to the possible expansion of the scope of application in sustainable economic development. To date, bio-economy has become an interdisciplinary and interdisciplinary field with a large number of identified development vectors.

Bran and Dobre note that the bio-economy's interdisciplinary characteristics make it possible to solve certain environmental and socio-economic problems [5]. Biology, biotechnology, environmental and engineering sciences, economics, management and information technologies are the main fields of knowledge formulating the bio-economy concept defined by Bugge [6]. Falcone and Imbert defined that new promising opportunities for bio-economic transformation are formed due to demand growth and rapid development of bioproducts and bioproduct markets [7]. Development of markets and increasing demand for bio-products opens up new business opportunities, as well as the creation of sustainable chains of added value for biomass and bio-products, bio-energy, and related services, creating economic advantages and demonstrating the positive impact of the bio-economy on sustainable development [8]. The economic benefits of implementing bio-economic models are not always obvious, as they are challenging to measure due to the interdisciplinary nature of the bio-economy, different measurements of direct and indirect results at the micro and macro levels are sufficient, or even simply because of reliable statistical data [9]. The complexity of assessment and forecasting creates additional obstacles to implementing integrated bio-economy policies, management, and strategies at the national, regional, and local levels.

From the above, it was evident that developing an action, a comprehensive strategy for bio-economic transformation, is an extremely difficult. While there is already enough research in the academic community that addresses the concept of the bio-economy, other stakeholders, such as businesses and the public, often need more information and act intuitively, and their opinion is often leveled. One, perceptions, interests, and beliefs are altered depending on the sector the stakeholders belong to (e.g., agriculture or the technology sector).

In Ukraine, a bio-economic strategy has not yet been approved at the national level, although it is long overdue. The development of bio-economic policy and strategy is largely influenced by the perception of bio-economic transformation by key stakeholders: representatives of government bodies and academic/research institutions, as well as representatives of business and the non-governmental sector. The identified stakeholders have their roles; the state representatives involve decision-makers and can adapt the legislative framework, all directives, and policies, while the academic community conducts research and promotes the development of technology and innovation and is the main source of knowledge dissemination about sustainable development. The opinion of businesses and entrepreneurs cannot be neglected either, since they are the ones who implement the concept of bio-economy in life, in the real sector of the economy. In contrast, the public sector is responsible for the advocacy and dissemination of knowledge and informal education of citizens. Both categories of interesting pages contribute to the development of the business department and support the transition of citizens and consumers to sustainable consumption in the processes of bio-economic transformation.

In the world's scientific practice, there are many works [10] dedicated to the concept of bio-economy, from the beginning of its formation to its improvement as one of the concepts aimed at achieving the goals of sustainable development [11] and circularity [12]. At the research level, the bio-economy relies entirely on the development of science and technology. According to many researchers, all developed bio-economic strategies involve a technological innovation transition to the bio-economy [13]. In addition, bio-economy is also considered a driver of dynamic social transformation [14] and regional local development, especially for rural depressed areas [15], which requires consideration of the political aspects of bio-economic transformation. At the global level, the process of bio-economic transformation is held up by the desperate resistance of the world's giants engaged in the extraction of minerals [4]. Therefore, among other things, bio-economic transformation requires strong political will and well-formed dynamic initiatives [16]. For this, it is necessary to educate a new generation of politicians who will possess the appropriate in-depth knowledge necessary to initiate and support the bio-economic transformation at all levels [17]. Over the last decade, Ukrainian scientific thought has been significantly enriched by scientific works in the field of bio-economy: starting from the definition of the main components and advantages of bio-economy [18], its strategic priorities and institutional support for development in Ukraine [19], in particular in agriculture, to its development in the management system natural resources using advanced European experience [20].

The purpose of the article is to form a generalized vision of bio-economic transformation by the main stakeholders at the micro level based on the study of the perception of the concept of bio-economy for further consideration in the formation of policies and strategies at all levels of decision-making, development of curricula and disciplines, conducting scientific research in the context of Ukraine.

To achieve the research goal, we conducted an online survey to determine the level of bio-economic perception, its advantages, problems, and prospects by various stakeholders in the academic environment, industry, business, civil society, and the public sector. The survey was conducted through different target groups, including business and industry representatives, governmental and non-governmental organizations, and research, innovation, and educational institutions, to understand their perception of the bio-economy and its benefits and threats. In particular, the survey aimed to achieve six target results: to understand how business, science, and political actors perceive the bio-economy; review value chain priorities and related communication activities; identify obstacles and conditions for supporting bio-economic transformation; assess the "willingness to cooperate" with the bio-economy; get information on how to improve cooperation between government, science, and industry; find critical points of influence on the development of the bio-economy by identifying overlaps with other areas of state policy.

To achieve the research goals, we have developed a scientific and methodological approach that can be used as a basis for socio-economic justification and development of strategies for the bio-economic transformation of socio-economic systems in Ukraine and further prospects for their implementation. The scientific and methodological approach we propose involves using a mixed research design. In the first stage, we used a qualitative method of research, which is not the subject of this study, the results of which formed the basis of the second, quantitative stage of the study, during which the conclusions obtained from the qualitative part were further investigated and transformed into a quantitative expression. The qualitative research method used in the first stage is focus group moderated sessions held in an expert environment of representatives of Ukrainian science, business, state and public sectors, and companies in selected industries. At the stage of implementation of the second quantitative part of the research, the method of surveying a wide range of interested persons was used, and questionnaires were formed based on the results of the qualitative stage of the research. In our study, focus group experts are managers of certain strategic areas of development of the organizations under study. The selected respondents for the online survey are employees of organizations related to business, educational and scientific institutions, and the state and non-state sectors, who are directly related to the general processes of transformation of organizations through management decision-making. From a managerial point of view, an expert at this level possesses information that allows for certain conclusions regarding the organization's perception of strategic aspects of bio-economic transformation and related risks and opportunities.

A multi-stage stratified sample was used to select organizations based on the sub-industry's characteristics and the organization's size. The selection of respondents was carried out randomly within each stratification group. The number of respondents for the survey is determined separately for three groups: business, research and educational organizations, and public and non-governmental organizations. The selection of the number of respondents from the general list is mainly carried out using a random number generator. As a result, a list of respondents to be surveyed has been formed. The research task did not involve the determination of any mathematical dependencies but only quantitative testing and visualization of trends determined in focus group studies, within which assumptions about the qualitative patterns of the process were determined. When processing the questionnaire survey results, we used graphic representation methods. Graphic representation gives the most visual presentation of the obtained results, allows to understand better the physical essence of the perception of bio-economy by various stakeholders, to reveal the general nature of the functional dependence of the studied variables, to establish connections between trends.

This research structure and concept provided an opportunity to test and quantify the results of qualitative research. The advantages of the proposed methodological approach are the improvement of the perception of qualitative parameters of the parameters of the researched topic by its quantitative addition, as well as in the ease of its implementation and interpretation. The shortcomings of the proposed research are insufficient consideration of the regional context because the perception of bio-economic transformation and its main directions often depends on the natural resource potential of the respondents' region of origin and the relatively small sample of respondents. However, considering the sufficiently high expert background of the surveyed respondents, the obtained research results can be useful for a wide range of interested parties, and the developed methodology is used for conducting additional regional, larger-scale studies.

2. Perception of bio-economy in business, politics and science

A total of 131 people took part in the survey, 63 respondents of which classified themselves as "scientific research, innovative, educational institutions" (48.1 percent), 36 respondents – from the category "government (the relevant public sector) or non-governmental organizations" (27.5 percent), 32 people from "industry and business" (related private sector) (24.4 percent). 33.6 percent of respondents were men, 65.6 percent were women, and others preferred not to answer. The respondents were representatives of all age groups except for those 65+ years. The majority of respondents belong to the age group of 35-44 years (41 percent of respondents) and 45-54 years (22 percent). The majority of respondents live in urban areas (78 percent), compared to those who live in rural (12 percent) or semi-rural/suburban areas (10 percent). Most respondents answered that they are very familiar with the bio-economy concept, with 13.7 percent indicating a high level of awareness and 60 percent meaning that they have an average knowledge of the bio-economy. 26 percent of respondents reported that they know absolutely nothing about the bio-economy. In the first part of the survey, respondents were asked questions about the concepts and sectors that, in their opinion, can be considered as part of the bio-economy, what are the main advantages and risks of the bio-economy in their region, and what is the level of awareness of the bio-economy among the population. Circular use of biomass (76 percent of respondents), use of biomass for different purposes (70 percent), ecosystem services (62 percent), sustainable land management (59 percent) and sustainable consumption (53 percent) are the main concepts that are most often considered as part of bio-economy (figure 1).

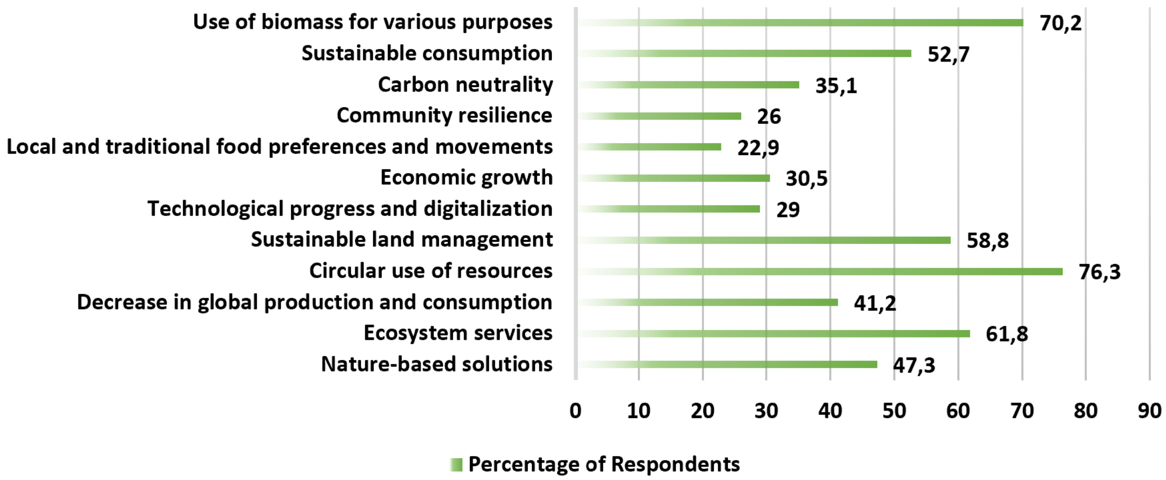

Figure 1. Sectors of the national economy, as a component of the bio-economy, percentage of respondents.

Interestingly, less than 50 percent of respondents associate the bio-economy with the implementation of nature-based solutions (47 percent), the reduction of global production and consumption (41 percent) and economic growth (30.5 percent), technological progress and digitalization (29 percent), carbon neutrality (35 percent), local and traditional preferences and movements, and community sustainability have the lowest affiliation (23 and 26 percent, respectively).

It can be concluded that the respondents associate the increase in the use of biomass for various purposes, the implementation of circular economy principles, the growth of ecosystem services, and the sustainable management of land resources with the bio-economic transformation. On the other hand, bio-economic transformation is considered less relevant for economic development, technological progress, digitalization, and the sustainability of local communities. In terms of primary production, the bio-economy is more associated with agriculture (85 percent) than with forestry (76 percent), fisheries, and aquaculture (56 percent) (figure 2). A significant proportion of respondents consider waste processing, biotechnology, and pharmacology as part of the bio-economy (66 percent each).

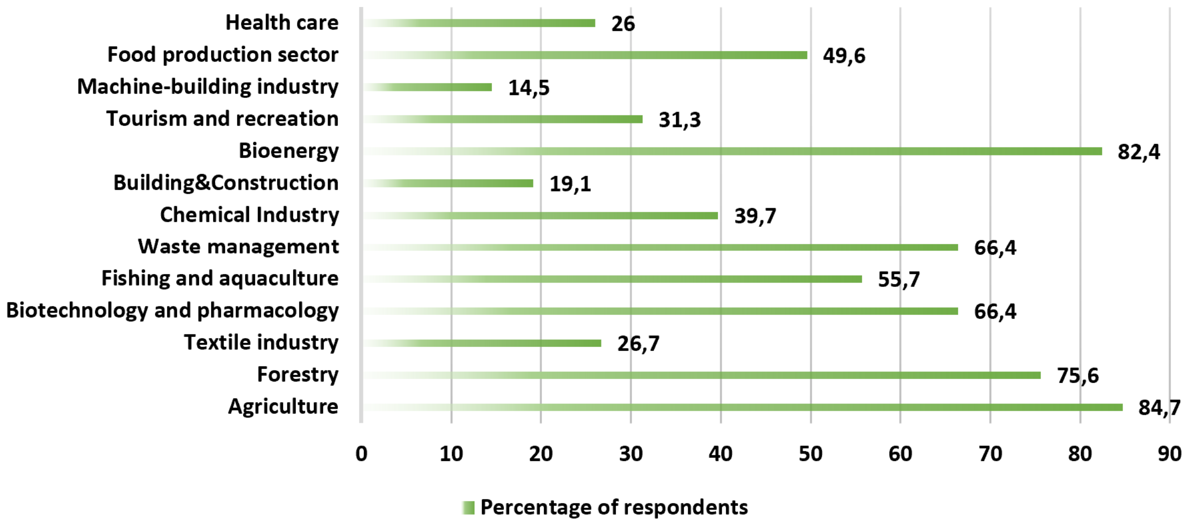

Figure 2. Sectors of the national economy, as a component of the bio-economy, percent of respondents.

Among the sectors of the processing complex, the most attention is paid to bioenergy (82 percent), the food industry, and gastronomy (50 percent). Chemicals (40 percent), tourism and recreation (31 percent) are other secondary industries that more than a third of respondents consider to be part of the bio-economy, followed by the textile industry (27 percent) and healthcare (26 percent). The construction and mechanical engineering sectors (19 and 14.5 percent, respectively) are the least correlated with the bio-economy. In addition, almost 3 percent of respondents determined that all the listed sectors are part of the bio-economy – everything depends on technology. As shown in Figure 3 below, based on the level of correctness of relevant statements characterizing the bio-economy, the vast majority of respondents (85 percent) agreed with the positive impact of the bio-economy, such as that the bio-economy provides opportunities for business and innovation, contributes to sustainable economic development, provides advantages for the development of rural areas, helps mitigate climate change, creates new jobs. More than 95 percent of respondents agree that the bio-economy offers opportunities for business and innovation, promotes sustainable economic growth, and helps mitigate the effects of climate change.

On the other hand, about 25 percent of respondents note some risks of the bio-economy, namely increasing the load on natural systems and causing deforestation. Slightly less than 50 percent of respondents note that there is not enough biomass for bioeconomic transformation.

When evaluating the most important benefits of the bio-economy, the most frequent answer is the reduction of raw materials and waste usage, the promotion of reuse and recycling (47 percent), followed by the reduction of the preservation of biodiversity and ecosystem services (19 percent), renewable energy to replace fossil fuels (12 percent), renewable alternatives to non-renewable materials (10 percent), transition to a low-carbon economy (6 percent). The lowest indicators received such benefits as creating jobs and economic growth (2 percent), ensuring people's well-being (3 percent) or promoting technological innovation (2 percent).

When assessing the risks of the bio-economy, the most common answer is "Insufficient biomass to support the bio-economy" (19 percent). 17.6 percent of respondents indicated that the most critical risk is the increase in the cost of essential goods (for example, food, water, housing, etc.) and the negative impact on ecosystem services (16 percent). Fewer respondents considered the impact of biomass imports from Europe (11.5 percent) and the increase in biomass costs (10.7 percent) significant. The smallest number of respondents noted the possible negative impact of the bio-economy on poverty or food sovereignty (6 percent). A significant proportion of respondents (18 percent) indicated that none of the predefined risks was the most critical risk.

3. Improving communication strategy and prioritization for values

The questions of this section related to the extent to which Ukraine is ready for the transition from a traditional economy to a circular bio-economy, the identification of bio-economy sectors with the highest potential for development, and to what extent different sectors can replace fossil raw materials with biological materials in the region by 2050. The answers we received allow us to review value chain priorities and related communication activities and compare them with existing bio-economy sectors and development strategies.

When respondents were asked how they assess Ukraine's readiness to transition from a traditional economy to a circular bio-economy, the majority of respondents answered that it is medium readiness (44 percent of respondents), high readiness, and very high readiness (5 percent, and 2 percent of respondents, respectively) and low readiness and very low readiness (31 percent and 16 percent, respectively) (figure 3).

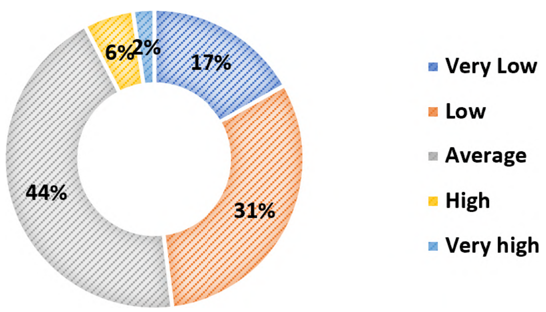

Figure 3. Perception of Ukraine's readiness to transition from a traditional economy to a circular bio-economy.

According to the respondents, bioenergy has the most significant potential in Ukraine's bio-economy (72 percent), corresponding to the region's vision of energy transformation. The agri-food sector (60 percent), green tourism (43 percent), bioplastics (36 percent), new advanced biomaterials (34 percent), green chemistry (24 percent), and the food sector (28 percent) were noted by respondents as having medium potential. The sectors with the lowest potential in Ukraine include pulp and paper (11 percent), textile industry (5 percent), wood products and furniture (8 percent), and non-wood forest products (for example, mushrooms, resins, etc.) (14 percent). Also, one of the respondents added a category that he considers the most promising sector – the development of green hydrogen in Ukraine. In this section, respondents were asked to predict how much six selected sectors of the economy can replace fossil raw materials with biomaterials by 2050 in Ukraine. Table 1 shows that more than 40 percent of respondents believe that the sectors of "Energy", "Textile industry", "Manufacturing industry" and "Food processing and packaging" can replace with biomaterials more than 50 percent of fossil materials/raw materials (50-70 percent, 70-90 percent, and 90-100 percent) by 2050 in Ukraine (figure 4).

As for agro-processing, trade, and food packaging, more than 60 percent of respondents think so – that is, the most potentially likely option.

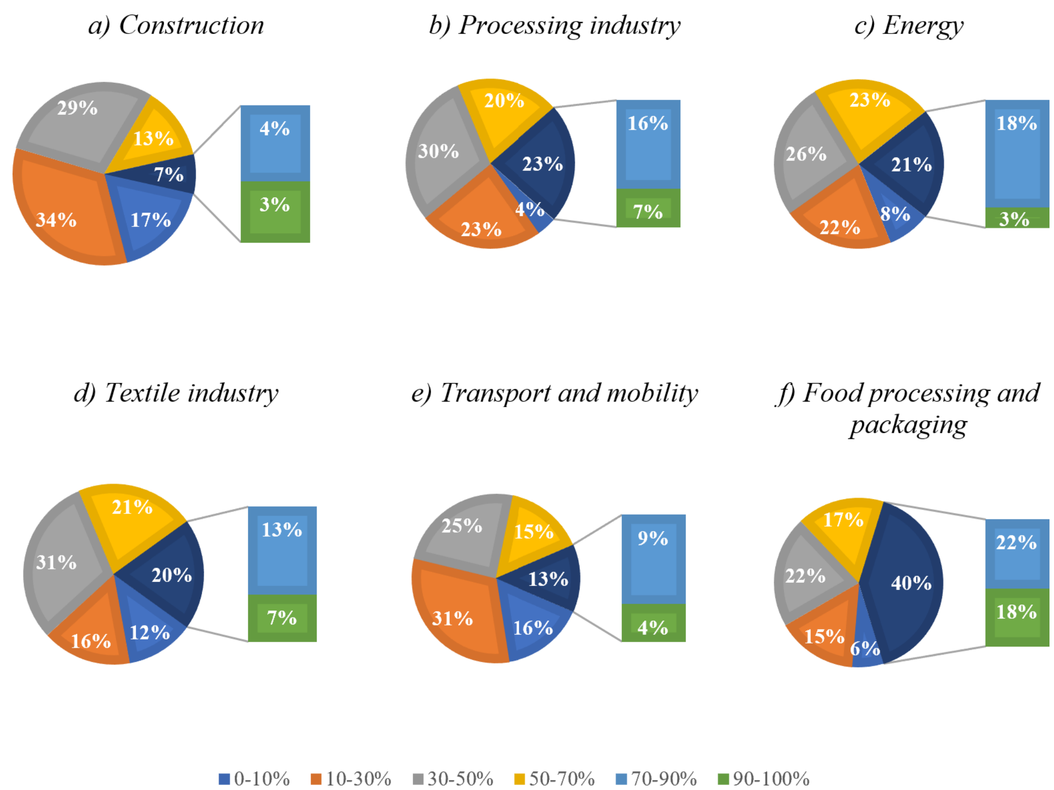

Figure 4. Perception of the prospects of replacing fossil raw materials with biomaterials in selected sectors of Ukraine's economy by 2050.

Using averages over a range of predefined proportions (e.g., assuming that respondents who chose 10-30 percent on average believe that about 20 percent of conventional materials are replaceable), we can estimate the average proportion of fossil raw materials/materials that can be replaced with biomaterials. The result of this study is that the agro-food sector is, on average, estimated to be the sector with the highest potential for replacing fossil raw materials with bioresources in Ukraine by 2050. Namely, 57 percent of resources are estimated as replaceable. The second sector with the largest share of replaceable resources is the manufacturing sector, with 48 percent. In third place is the energy sector, with 46 percent, and the textile industry, with 45.6 percent.

4. Analysis of potential obstacles and mechanisms for supporting bio-economic transformation

The issues of this survey section are related to the definition of favorable conditions and possible obstacles to developing the bio-economy in Ukraine. The information obtained allows you to ensure compliance with the most important conditions of support and to develop strategic decisions to overcome barriers to bio-economic transformation.

The most important factor supporting bio-economic transformation in Ukraine is the availability of information for the scientific justification of political decisions, investment in innovation, and adequate state regulation to overcome possible negative consequences for the ecosystem and local communities. These factors were rated as important and very important by more than 86 percent, 85 percent, and 84 percent of the surveyed respondents, respectively (figure 5). Public procurement and carbon tax programs were rated as important and very important by more than 70 percent of respondents.

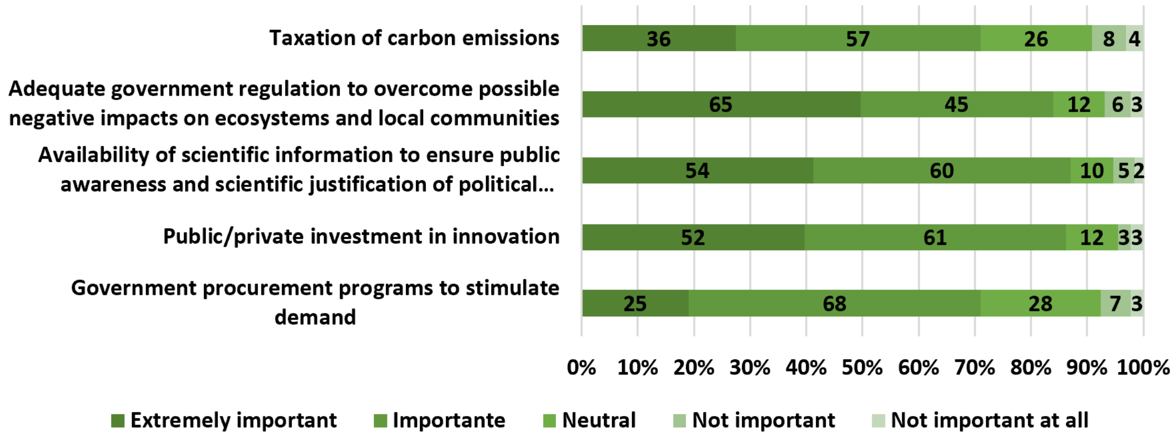

Figure 5. Perception of factors supporting bioeconomic transformation in Ukraine.

Regarding the perception of obstacles to bio-economic transformation, one of the most important obstacles noted by the largest number of respondents is the lack of favorable state policy and legislative support adapted to regional needs. More than 85 percent of respondents have this opinion. A little more than 80 percent of respondents consider the lack of cooperation between various interested parties (for example, politicians, business, and scientific environment) as a very important or important factor (figure 5).

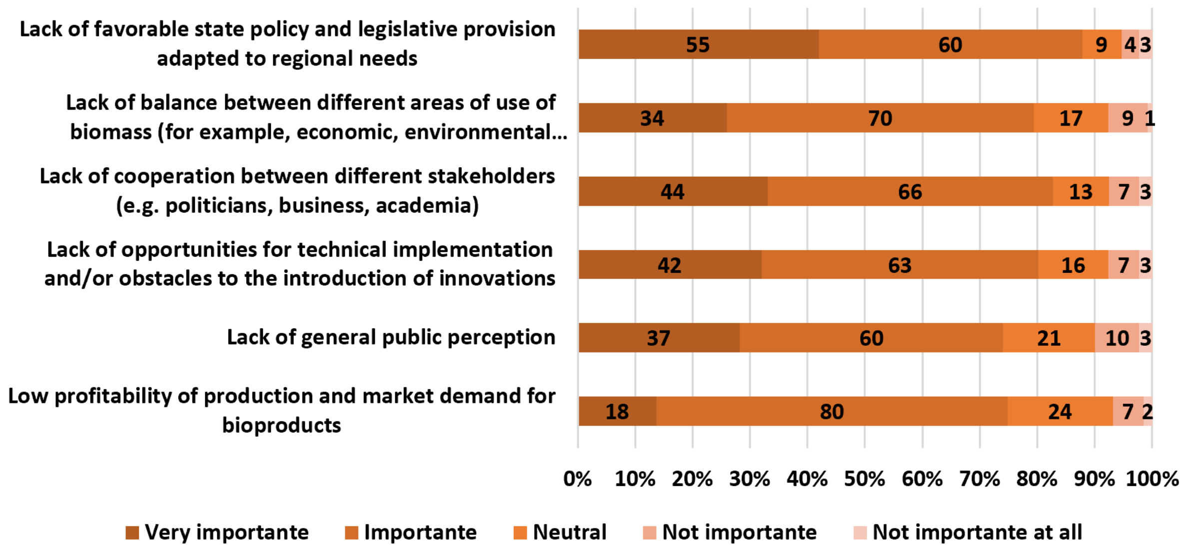

Figure 6. Perception of factors hindering the development of the bio-economy in Ukraine.

Two other obstacles, the lack of balance between different areas of biomaterial use (for example, economic, environmental protection, carbon absorption, etc.) and the lack of opportunities for technical implementation and/or obstacles to the introduction of innovations, were supported by 80 percent of respondents. Low profitability of production and market demand for organic products and the lack of general public perception are recognized by more than 75 percent of respondents as important or very important. However, suppose the lack of public perception is considered a very important factor for more than 25 percent of respondents. In that case, low profitability is only for a little more than 10 percent of respondents.

5. Analysis of readiness for active implementation of bio-economic vectors of development

In this section, respondents answered questions about the readiness of a scientific institution, industrial enterprise, government agency, or state institution to develop the bio-economy; the involvement of the organizations they represent in the implementation of any investment projects, regulation or initiatives related to the bio-economy, as well as the main reasons for their participation in such projects. Below are the results for the three surveyed categories of respondents (figure 7).

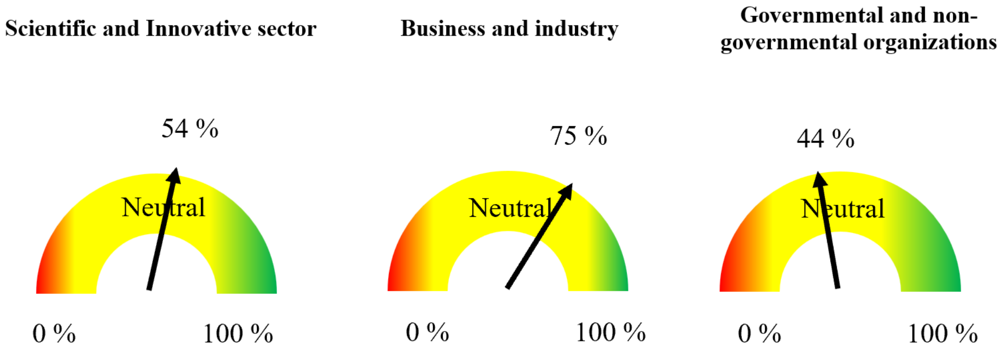

Figure 7. Perception of factors hindering the development of the bio-economy in Ukraine.

The representatives of the scientific and innovative sectors were asked a question regarding their sense of readiness of their sector for the development of the bio-economy. About 29 percent of respondents declared 100 percent readiness, 16 percent of respondents noted that their sector is not at all ready to develop the bio-economy, while the largest part (54 percent of respondents) expressed an opinion about an average level of readiness. 20 percent of respondents testified to the fact that their organizations implement, or have implemented in the past, investment bio-economic projects. The main reasons for their implementation were the following factors in descending order: to use state support mechanisms, to use existing market opportunities, and to obtain competitive advantages in the market. 50 percent of respondents named the lack of technical capabilities as the main obstacle on the way to the implementation of bio-economic projects. In second place is high uncertainty in bio-economic projects and the immaturity of the market (27 and 22 percent, respectively). Low expected profitability defined about 11 percent of respondents from implementing bio-economic projects in science. The fact that conducting research and development in the bio-economy has some state support is obvious, and the negative side of innovative bio-economic development is also observed – the lack of technical capabilities for implementing investment bio-economic projects in the scientific and innovative sector. According to the survey research results, the largest number of respondents from business and industry attest to an average level of readiness for bio-economic transformation – 75 percent – which means that respondents from business and industry are more likely to develop the bio-economy. However, only 7 percent of those consider themselves 100 percent ready for this, while 19 percent of respondents were not ready at all for bio-economic transformation, which is probably related to a specific field of industry. 28 percent of respondents from business and industry stated that they had implemented investment projects in the bio-economy in the past.

The main reasons for the implementation of investment projects in the bio-economy by representatives of business and industry are the use of existing market opportunities (100 percent of respondents from business and industry who implemented projects in the field of bio-economy), to obtain competitive advantages in the market (67 percent), the use of state support mechanisms (33 percent), several respondents noted such incentives as saving resources and reducing the cost of goods and services. The main reasons for dealing with bio-economy projects were immaturity of the market (40 percent), followed by high uncertainty of bio-economy projects (34 percent), low expected profitability, and lack of technical capabilities noted by 30 percent of respondents. Respondents had the opportunity to choose several possible reasons and incentives. Summarizing, we can emphasize the fact that most representatives of business and industry do not have information about any mechanisms of state support for bio-economic projects, and all of them implement such projects to use existing market opportunities. The respondents of this group were asked how ready they were to develop the bio-economy on a scale from zero (I have no desire) to one hundred (I really want to). The average level of expressed desire was confirmed by 44 percent of respondents from the governmental and non-governmental (public organizations) sectors, which means that the position is more neutral than that of the two previous groups of respondents. However, 100 percent readiness to support the development of the bio-economy was shown by 33 percent of respondents (half of whom are from the public sector), 22 percent were not ready for bio-economic transformation at all, of which only one respondent belonged to the public sector, the rest to the non-governmental organizations. In addition, only 19 percent of respondents from the governmental and non-governmental sectors confirmed participation in investment projects in the bio-economy, most of which are, however, representatives of the public sector.

The main incentives for the development of investment bio-economic projects are considered to be the use of state support mechanisms (almost 50 percent of the respondents who participated in the implementation of such projects), 46 percent and 38 percent, respectively, attributed them to the incentives of obtaining competitive advantages and using existing market opportunities. The lack of technical capabilities and the immaturity of the market are the main restraining factors (36 and 28 percent of the surveyed respondents share this opinion), a slightly smaller number of respondents (17 and 19 percent, respectively) consider high uncertainty in bio-economic projects and low expected profitability as important factors.

However, when we ask the question from a different angle to all three groups of respondents, namely: to what extent is the public sector ready to develop the bio-economy? We have somewhat more pessimistic predictions, especially regarding the perception by business and industry of the public sector's readiness to develop the bio-economy. 50 percent of respondents consider the public sector not ready to implement bioeconomic transformations, while the other half assesses the level of readiness as average. In this block of questions, a high level of government readiness for bio-economy development was not confirmed by any group. In particular, in the groups of science and innovation and the governmental and non-governmental sectors, there were 2 such respondents from each group. In contrast, in the business and industry group, no respondent voted. However, only a third of the industry and governmental/non-governmental groups of respondents are aware of any developed regulations or initiatives related to the development of the bio-economy. More than 63 percent of respondents of all groups do not know anything about the developed regulatory and legislative initiatives related to bio-economic transformation.

Ensuring sustainability or social justice (60 percent of respondents), creating markets and social acceptance of bio-economy products (50.8 percent), as well as improving provision and access to biological resources (38 percent) are defined as the main goals of developing relevant regulatory acts or initiatives regarding bio-economic transformation. In addition to the proposed goals, the respondents identified the implementation of the European Green Course and the declarative nature of individual draft laws as two of the goals.

Among the main obstacles of the bio-economic transformation initiatives, the most common opinion is the lack of financial opportunities (52.7 percent) and the lack of such goals on the agenda of local strategies and policies (48.4 percent), 43 percent of respondents also noted the lack of a request from society for such initiatives, and 30 percent noted that regional development plans do not contribute to the development of the bio-economy. Instead, some of the respondents indicated additional negative factors restraining the development of the bio-economy, namely, lack of systemic vision, planning and forecasting, corruption of officials, and attempts to open the land market in Ukraine.

We have summarized six key statements about the perception of the bio-economy in Ukraine.

1. The bio-economy is considered to have great potential for business development and innovation, promotes sustainable economic development, benefits rural development, helps mitigate climate change, and creates new jobs. Still, its potential for economic and innovative growth appears to be less visible.
2. Among the respondents, there is a firm belief that the public needs to be sufficiently informed about the bio-economy and its development prospects in Ukraine.
3. The most promising sector from the point of view of bio-economic transformation is agriculture – in the primary sector and bioenergy – in the processing sector of Ukraine.
4. Readiness for the bio-economic transformation of industry sectors by 2050 in Ukraine remains average, with the most promising areas in agro-processing and retail trade (food packaging).
5. Most of the proposed favorable conditions are considered key factors for the development of the bio-economy. In contrast, the main negative factor remains the lack of favorable state policy, and legislative support adapted to regional needs.
6. The scientific and innovative sector and the business environment show a higher readiness for the development of the bio-economy than the public sector. Still, all areas are quite consistent in their understanding of the areas of responsibility.

The results of the online survey indicate that the bio-economy, as the next wave of economic growth, is perceived quite positively by all groups of stakeholders involved. Among the respondents, there is an understanding of the potential opportunities that the bio-economy transformation opens up, such as the creation of new jobs, the opening of new markets, and increased competitiveness. A significant part of respondents confirm the importance of the role of bio-economy in the sustainable development of socio-economic systems in Ukraine. The economy of scale, networking, reuse, and processing of bioresources and their waste, combined with appropriate financing mechanisms, are considered important elements of an effective transition to bio-economic business models and in forming new strategic competitive advantages for organizations. It is important to note that some statements were obvious to academics in specific fields. At the same time, respondents from business and government organizations had different views, so it is important to conduct deeper analysis and further research, considering all stakeholders' perspectives. It can be concluded that most categories of stakeholders work in isolation, which prevents the achievement of synergy effects and the possibility of uniting around the intended perspectives and desired results. According to the perception of the interviewed stakeholders, Ukraine's bio-economy is closely related to the use of biomass and the sustainable and efficient use of natural resources. Expanding information, knowledge, and government support are critical elements of policy development in conjunction with technological and industrial development. According to the results obtained, the Ukrainian adapted version of bio-economic transformation (in a broad sense – sustainable, circular bio-economy) can be implemented by overcoming isolation and ensuring multilateral cooperation between various scientific fields, technologies, institutions and organizations using a synergistic approach. Such initiatives should be supported by appropriate public and private funding mechanisms and be based on science-based strategies and plans, as creating innovative and sustainable value-added chains requires significant investment, research support, innovation development, and compliance with the principles of circularity and resource efficiency. The results of the study demonstrate the urgent need for the creation of interdisciplinary and interdisciplinary working groups for the formation of a national strategy for bio-economic transformation in Ukraine, the development of specific policies that may relate to the improvement of interdisciplinary and intersectoral communication, and the promotion of the concept of bio-economy, its potential advantages and the analysis of necessary transformations at the entrepreneurial, technological, and legislative levels. Determinants of development and the identified risks of bio-economic transformation give the possibility to formulate the following recommendations for the development of a national bio-economy strategy in Ukraine:

1. Consistent development of the political background and comprehensive cross-sectoral vision of bio-economic transformation with the involvement of a wide range of interested parties.
2. Effective coordination with regional, national, and European policies.
3. Investing in stimulating the acquisition of new knowledge and the implementation of modern approaches, the introduction of innovations at all levels of the bio-economy, the reduction of interdisciplinary and intersectoral isolation and the formation of heterogeneous working groups of experts for decision-making and policy development to expand the strategic vision and form the mechanisms of bioeconomic transformation.

Such an approach will provide an opportunity to eliminate inconsistencies between fields of science, priorities of scientific research, political vision, practical initiatives, and legislative support. A coordinated interdisciplinary and interdisciplinary approach can contribute to the comprehensive development of the bio-economy based on sustainable development by ensuring the development and implementation of new technologies by the local characteristics of the region. The development of strategies in this way will enable the conscious movement of production and economic activity from “sectors” to “socio-economic systems” or “sustainable value-added chains” due to the establishment of constructive network ties of the relevant economic and production sectors to ensure a closed cycle of deep processing bioresources.

6. Conclusions

The cross-cutting nature of new bio-economy models determines various stakeholders’ excellent perception of bio-economic transformation. On the other hand, the perception of the bio-economy by key stakeholders has a significant impact on the development and implementation of relevant transformational mechanisms. The survey results provide an opportunity to analyze the level of perception of the bio-economy in Ukraine, its advantages, and the challenges associated with the bio-economic transformation by representatives of the academic community, public sector, and civil society at the local level, and business. The results of the conducted research on the perception of bio-economic transformation by various interested groups of stakeholders will be important for determining the priorities of regional bio-economic strategies for policy development and communications to maximize the effectiveness of their impact. We have summarized six key statements about the perception of the bio-economy in Ukraine. Empirical results indicate the need to develop a coherent cross-sectoral and interdisciplinary approach to knowledge, skills and competencies for the proper bio-economic development on the basis of sustainability, the development and use of innovative technologies, taking into account national and regional characteristics. The study contributes to the expansion of the discussion on the need to implement the concept of bio-economy in Ukraine and fills the scientific gap in the perception of bio-economic transformation by various stakeholders at the micro level.

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Transforming education: Navigating the human-AI ecosystem in psychological training and beyond

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Abstract. This article explores the dynamic impact of artificial intelligence (AI) on education, with a focus on its integration into the field of psychology. The study analyzes the dichotomous nature of AI in educational settings, highlighting both its potential for innovation and the challenges it presents, particularly in terms of academic integrity and the quality of training. Utilizing the concept of self-organization of systems, the article examines AI as a transformative factor in education, necessitating a new order of collective interaction among educational participants. Empirical research is presented, comparing the content, structure, and style of texts generated by AI (specifically Claude 2.1 and ChatGPT 4) and psychology students. This comparison establishes criteria for differentiating between "human" and "artificial" texts, underscoring the unique aspects of human creativity and critical thinking that AI currently cannot replicate. The study also reveals the evolving role of educators as facilitators within a hybrid ecosystem of human and AI participants. The article proposes future research directions, including the exploration of collaborative interactions between individuals and AI and the development of accelerated learning methodologies within the human-AI ecosystem. It emphasizes the necessity of balancing the strengths of human creativity with AI's computational efficiency, aiming to enhance student motivation and expand cognitive capabilities in educational settings. Furthermore, the article discusses the emergence of new professional roles such as AI user facilitators, and AI facilitators, highlighting the growing complexity of human-AI interactions. These roles are crucial for effective and ethical utilization of AI in education, especially in psychology. The article presents AI as a catalyst for significant paradigm shifts in education and professional training, particularly in socionomic fields. It advocates for a synergistic approach to education, where AI complements human abilities, leading to enriched learning experiences and the development of a more adaptive, personalized, and efficient educational landscape.

1. Introduction

The integration of artificial intelligence (AI) in education, particularly in psychology, is crucial for shaping a sustainable future. By enhancing the training of future psychologists, AI can equip them with the skills and knowledge needed to address complex sustainability challenges. As psychologists play a vital role in promoting sustainable behaviors and well-being, the responsible incorporation of AI in their education can better prepare them to contribute to sustainable development. Moreover, the ethical integration of AI in psychology education serves as a model for other disciplines, demonstrating how technology can support sustainability goals without compromising essential human elements in the learning process.

2. Literature review: AI and emerging trends in education

The integration of AI in education, a field historically advocating for more authentic and individualized teaching and assessment methods [1], has introduced both exacerbation of existing challenges and new opportunities. Recent literature highlights several emerging trends in this domain, centering on attitudes towards AI, its potential impacts on individuals and society, and the dynamics of its development, along with necessary actions at various levels ranging from international to organizational [2–7].

A prominent trend is the academic community's concern regarding the potential for fraud and violation of academic integrity, triggered by the use of AI technologies in writing educational and scientific papers [8]. Another trend is the reformation of learning and assessment methodologies through AI technologies [9], though their effectiveness for technical specialty students is debated [10]. Moreover, the adaptation of various professions, including teaching and research, to the evolving AI landscape is actively being explored [11–13].

A further trend involves the automation of routine educational tasks, such as test checking and content preparation, through AI tools like chatbots. This aims to strike a balance between automation, human capabilities, and AI, ultimately freeing up time for creativity and personalized learning [14–16]. Additionally, the development of AI regulatory policies in general [17], particularly in science [18], and education [19], is being closely examined. However, there is a caution against over-regulation from innovation advocates like Roose [20], who argue it could stifle AI development and limit educational prospects. Soft regulatory mechanisms, such as ethical principles and self-regulation by educational and scientific organizations, are also under consideration [21, 22].

3. Theoretical substantiation: from AI chaos to a new order in education

The advent of AI in the educational landscape has disrupted the traditional linear progression of educational system evolution. This disruption is evident in the emergence of both long-maturing and entirely novel trends. This non-linear development process, when viewed as a self-organization of education, underscores the infeasibility of maintaining the status quo. The future shape of the education system remains indistinct, with its contours likely to emerge retrospectively upon the completion of this transition. This break in gradualness signifies a rhythm of self-organization in the education system, transitioning from the former SPOD (Stable-Predictable-Orderly-Definite) model to a VUCA (Volatile, Uncertain, Complex, Ambiguous) educational environment. This shift, often perceived as chaotic and unpredictable, leaves students, educators, and educational administrators without a clear trajectory for immediate educational development.

In the context of Vygotsky's developmental zones theory, these phenomena align with the concept of a 'buffer development zone', characterized by high energy and potential for exploring new self-organization forms [23]. The emergence of a new order in education represents a synthesis of foundational elements for the system's existence, following a developmental model of thesis-antithesis-synthesis, indicative of a robust self-organizational process.

Analogous to the healthcare and education system transformations during the COVID-19 pandemic, AI, similar to the virus, has acted as an agent of chaos, catalyzing fundamental changes in treatment, education, and management approaches. We are currently witnessing these transformations.

Presently, the educational system is likely in a phase analogous to producing "antibodies" against the "AI virus", transforming it into a positive entity or "enhanced immunity of the social education system" [24]. At this stage, any attempts to inhibit the actions of teachers and students are seen as slowing down development. However, paradoxically, these actions also contribute to system evolution under the principle of "preservation innovation", which posits that innovations don't obliterate the past but rather reaffirm it in new forms.

The rapid proliferation of AI, exemplified by tools like ChatGPT 4 and Claude 2.1, has facilitated a non-linear management approach in educational and pedagogical processes, characterized as eco-centered psychological facilitation (ECPF). Given the necessity for students, teachers, and researchers to significantly adjust their methodologies, this situation presents an opportunity not only to assess the potential of a natural experiment in all aspects but also to expedite the learning process by embracing these changes.

The primary research objective is to investigate the potential of AI technologies in the training of psychology students and to explore the possibility of integrating these technologies into the educational process to enhance the quality of training for modern specialists. To achieve this objective, the following research questions were addressed: What are the distinguishing characteristics of essays written by psychology students compared to those generated by AI chatbots like Claude 2.1 and ChatGPT 4? What criteria can be used to differentiate between human-written and AI-generated texts in the context of psychology education? How can AI technologies be effectively integrated into the educational process to augment the training of future psychologists?

This integration aims to enhance the quality of training for modern specialists, aligning with the evolving educational landscape. The focus is on understanding how AI can be optimally utilized to foster a more efficient, adaptive, and individualized educational environment, responsive to the dynamic needs of students and educators alike. This exploration into AI's role in education represents a critical step towards navigating and shaping the future trajectory of educational development and innovation.

4. Methodology

In addressing the challenge of self-organization within the education system, triggered by the advent and rapid proliferation of artificial intelligence, a dynamic methodology was adopted. This approach acknowledges the dialectical relationship between AI and human intelligence, recognizing the emergent tension and potential crisis. Resolving this crisis is seen as an opportunity for the integration of AI and the holistic development of the educational ecosystem.

This study observes the spontaneous formation of new problem-oriented groups across various disciplines, including psychology and pedagogy. These groups are characterized by their non-linear approach to transitioning towards a higher level of self-organization and functioning, embodying the concept of 'order through chaos'.

Participants in the study: included a diverse mix of human and artificial intelligences: master's degree students in psychology (31 individuals, average age 31±4.6 years, 16.1% male, 83.9% female), two chatbots (GPT 4 and Claude 2.1, chosen for their proficiency in creating text-based content and their widespread use), independent experts (2 psychology professors, 2 practicing psychologists, 2 Ph.D. psychology students) and research facilitators. All participants were aware of the capabilities of the GPT 4 and Claude 2.1 chatbots.

Procedure and tools. Participants were tasked with writing a creative essay on one of 100 proposed topics, without size limitations. The chatbots received prompts in Ukrainian, instructed to simulate a psychology student composing a creative essay. The essays' potential was assessed by independent experts, who conducted a "blind" analysis, focusing on content, structure, and style, to differentiate characteristics inherent in human-versus AI-generated works. This analysis facilitated the establishment of criteria for distinguishing between "human" and "artificial" texts and aided in developing a list of collaborative tasks suitable for the training of future psychologists.

Statistical processing: includes descriptives, frequency and carried out using the SPSS statistical package.

Research ethics. Informed consent was obtained from all participants for their involvement and the publication of the study's results, adhering to norms of anonymity and confidentiality. The personal data of the participants are not disclosed and will remain inaccessible in any publications or dissemination of the study's findings.

Using large language models (LLM). Language translation, text editing and implementation of a prompt developed by us, which distinguishes the roles and functions of the professionals (table 3), was carried out in collaboration with the Claude 2.1 chatbot, ensuring linguistic precision and coherence. This methodology provides a comprehensive framework for exploring the integration of AI in educational contexts, particularly in the training of psychology students, with a focus on ethical and effective utilization of AI technologies.

5. Comparative analysis of students' essays and Claude 2.1, ChatGPT 4

In response to the task, students selected 17 topics from the provided 100. Both chatbots, Claude 2.1 and ChatGPT 4, generated essays on these same topics, albeit shorter in length. The essays were then analyzed by experts and the chatbots themselves to identify authorship. Surprisingly, neither the experts nor the chatbots could accurately determine the chatbots' authorship. False identifications related to student essays were not further analyzed due to the inherent ambiguity in ascertaining their authenticity (table 1).

Table 1. Quantitative analysis of students' creative essays and chatbots.

Analyzed essay parameters	**Students**	**Claude 2.1**	**ChatGPT 4**
Number of essays	31	17	17
Number of topics	17	17	17
Average word count	352	186	104
Standard deviation	257	118	36
Mininimum word Count	82	163	37
Maximum word count	1071	201	149
Erroneous elections of experts, %	–	16.7	19.6
False picks Claude 2.1, %	–	29.4	17.6
False ChatGPT elections, %	–	17.6	29.4

Content analysis revealed that ChatGPT 4 essays were impersonal, relayed well-known academic knowledge, and provided stereotypical answers with general advice. These essays were deemed simple in terms of semantic, syntactic, and stylistic complexity, lacking originality, thesis, and antithesis. Claude 2.1's essays were more personalized, sometimes using first-person narratives, including appeals to experience, arguments from academic psychology, alternative judgments, generalized advice, conclusions, and rhetorical flourishes. In contrast, the future psychologists' essays varied greatly in content and length, but most exhibited elements of creativity, metaphor, unique style, emotional personal coloring, reflection, and a strong personal perspective.

The task of discerning the authorship of the texts proved straightforward in some instances and challenging in others for the experts. It was later determined that the presence of originality, multi-dimensionality of meanings, creative elements, and pronounced linguistic stylistics were convincing indicators of human authorship. A notable characteristic of human-written essays was the ability to present a detailed psychological portrait of the author.

This study demonstrates that while it is currently challenging to unequivocally determine the authorship of texts, certain criteria can be identified to make educated guesses. The presence of multiple relevant features in an essay increases the likelihood of accurately predicting its authorship (table 2). The criteria listed in table 2 for distinguishing between human-written and AI-generated essays were derived from a comprehensive content analysis conducted by a panel of experts.

Table 2. Criterion features of a human and AI essay.

Criterion	**Signs of an essay: man**	**Signs of an essay: Claude 2.1, ChatGPT 4**
Psychological portrait of the author	Holistic, convincing, imaginable	Difficult or impossible to imagine the author, dubious
Critical thinking	Deep understanding, correlation of data, subjective opinions with reasoning, marking ambiguous aspects	Surface-level, known facts, unambiguous interpretations
Linguistic complexity	Varied semantic, syntactic, stylistic complexity	Simple, repetitive, predictable
Structure of the text	Flexible, original	Template-based
Style and form of presentation	Variable, individual; personal appeals, reflections	Uniform, formal; impersonal, abstracted
Vocabulary	Rich, imaginative, unique speech patterns	Modest, standard, lacks stylistic uniqueness
Originality of content	Creative, original, personal reflections and judgments	Standard, known knowledge, lacks personal attitude
Creativity of ideas, argumentation	Original, creative, use of metaphors and figurative comparisons	Standard reasoning, limited creativity, minimal figurative language
Emotionality, attitude	Emotional, personal opinions and attitudes, topic significance	Emotionless, neutral, non-judgmental
Errors	Possible stylistic, grammatical errors, inconsistent logic	Substantive errors, generally consistent logic

The findings highlight the nuances in AI-generated versus human-written texts, especially in fields that require personal insight and creativity like psychology. This has implications for the role of AI in educational settings, particularly in tasks requiring personal expression and critical thinking. The study underscores the importance of developing and recognizing these unique human elements in education, even in an age increasingly influenced by artificial intelligence.

The results underscore the vast potential of the "human-AI" dynamic ecosystem in educational interaction. It suggests that the system of evaluation should shift focus from the end product (the essay text) to the process of its creation. This aligns with emerging professions such as prompt engineers or hybrid roles like prompt psychologists or facilitators, reflecting the intermingling world of human and AI interactions.

These professionals are envisioned to guide the creation of individual educational trajectories and foster self-help. The role of a human AI facilitator is envisaged as one who not only understands AI but also possesses expertise in the relevant subject area. For instance, in psychology, this would include knowledge of psychological counseling or psychotherapy basics, developing AI training exercises, and engaging in effective dialogue with AI. This role is about mastering a unique modality of psychological guidance, where the facilitator creates and adjusts AI assistants or agents to suit specific needs.

An AI facilitator is characterized by the ability to listen and understand both the capabilities and limitations of AI, without imposing their own decisions. They bear the responsibility for establishing a mutually comprehensible dialogue between humans and AI. The primary objective isn't to provide direct assistance to clients but to configure an AI assistant for mastering relevant psychological counseling skills. As the AI agent evolves, the facilitator must continually analyze and guide its development and self-improvement pathways, even to the point of "self-destruction" to lay new foundations for AI functioning.

This concept extends to non-linear management of learning processes and professional self-organization. In this context, we prompted ChatGPT 4 to differentiate the roles and functions of various professionals such as prompt engineers, AI user facilitators (specialists in user interaction with AI), and AI facilitators (specialists in AI development and adaptation to human needs) (table 3). This exercise aims to clarify and distinguish these emerging roles, highlighting the diverse skill sets and responsibilities required in a world where AI and human interactions are increasingly intertwined and complex.

The differentiation of roles in AI interaction and facilitation underscores the evolving landscape of AI integration in various fields, including education.

The distinction between professionals with and without psychological education becomes particularly significant. It emphasizes the need to perceive AI as a collaborative partner rather than merely a tool. This view shifts the perception of AI from an agent with dominating capabilities to an agent that understands and empathizes with human needs while maintaining its technological advantages. Such a perspective fosters a collective approach to civilization and bolsters social-psychological immunity.

In the realm of education, especially in the field of Educational Psychology, there arises a need to teach students to work not only with clients but also with AI. This emerging branch of study involves more than just employing AI in educational and assistance settings. It encompasses learning how to interact with AI, leveraging its capabilities to aid people. This approach is crucial for preparing future professionals to navigate an increasingly AI-integrated world.

Through this lens, AI is viewed as a collaborator in problem-solving processes, enhancing human capabilities rather than supplanting them. This collaboration marks a significant shift in educational practices and professional development, reflecting a holistic understanding of AI as an integral component of modern educational systems and psychological practices. This shift highlights the importance of fostering AI literacy and competency among students and professionals, ensuring they are equipped to effectively utilize AI in their respective fields.

6. Discussion of the results

The findings of this study align with other research on AI's capabilities in content generation and its limitations and advantages in science and creativity compared to human output [22, 25]. Our focus on humanitarian, psychological, and philosophical texts offer a different perspective compared to Tsidylo and and Esteve Sendra [26], who examined AI's potential in design. The observed specifics in ChatGPT text generation, such as lower creativity levels and limited logic, resonate with the findings of Lucey and Dowling [13], who noted ChatGPT's adequacy in generating scientific articles for journals.

Table 3. Roles and responsibilities in AI interaction and facilitation.

Aspect in AI interaction and facilitation	**Prompt engineer**	**AI user facilitator**	**AI facilitator**
Primary role	Designs and optimizes prompts for AI interaction	Assists and guides users in effective AI usage	Guides the integration and application of AI in specific contexts
Focus	Technical structuring of prompts	Enhancing user experience and engagement with AI	Ensuring effective use of AI in operational settings
Skills required	AI language models expertise, programming skills	Communication, user engagement strategies	Management skills, AI operational knowledge, problem-solving
Objective	Accurate AI understanding and response	User clarity and proficiency in AI interaction	Optimal AI usage in specific operational environments
Outcome	Efficient AI responses	Improved user-AI interaction and satisfaction	Effective and seamless AI integration
User interaction	With the AI system	With users, providing guidance and support	With operational teams using AI
Problem-solving	Technical (e.g., refining prompts)	User-focused (e.g., resolving usage challenges)	Operational (e.g., adapting AI to specific needs)
Knowledge base	AI systems, language processing	AI capabilities, user experience principles	AI applications in specific industries or sectors
Industry role	AI development or research	User support, training, education	AI integration in business or operational settings

AI and chatbots show promise for innovative learning forms, especially in student collaborations [12], and in the development of critical thinking skills [5, 20, 27]. This study further explores AI's role in analytical tasks for psychology students, contributing to the effective realization of AI's positive potential in education and training. This includes process optimization [28, 29] and the development of emotional artificial intelligence in future specialists [30].

The general potential of AI and chatbots in education, as outlined by sources like [14, 31], underscores the importance of our research in finding optimal ways to implement chatbots in the professional training of psychologists.

Despite AI's limitations in creativity and critical thinking, there is a consensus among researchers about AI's significant potential in education, enhancing the training system for specialists, and the need for further exploration of the educational potential of different AI models. Our study contributes to this body of research, particularly in the context of training psychologists, and suggests that the educational potential of various AI models for psychologists and other professionals warrants further investigation.

This discussion indicates a growing recognition of AI as a versatile tool in the educational sector, capable of complementing human efforts, especially in areas requiring high cognitive and emotional skills. It points to a future where AI is seamlessly integrated into educational practices, enhancing learning experiences while also addressing its limitations through ongoing research and development. The integration of AI in educational settings, particularly in psychology, offers an opportunity to revolutionize traditional pedagogical approaches, making education more adaptive, personalized, and efficient.

The study highlights the necessity for educational institutions and educators to adapt to these technological advancements. This adaptation includes not only the integration of AI tools into the curriculum but also the development of new pedagogical strategies that leverage AI's strengths while mitigating its limitations. It also underscores the importance of preparing students to interact effectively with AI, equipping them with the necessary skills to utilize these technologies in their future professional practices.

In summary, the role of AI in education, specifically in the field of psychology, is multifaceted and evolving. While AI can augment the educational process, its limitations in areas like creativity and critical thinking must be acknowledged and addressed. This balance between leveraging AI's strengths and compensating for its weaknesses is critical for the effective integration of AI in educational contexts. The future of educational psychology may well involve a symbiotic relationship between human cognitive and emotional capabilities and AI's computational efficiency, leading to enriched learning experiences and enhanced professional training. This evolving landscape calls for continuous research, development, and adaptation in educational methodologies to fully realize the potential of AI in shaping the future of education.

7. Conclusion

The integration of artificial intelligence into the educational landscape, particularly in the field of psychology, represents a paradigm shift in how education is delivered and experienced. Our study has illuminated AI's potential to revolutionize traditional educational practices, offering innovative, individualized, and efficient learning experiences. However, it also underscores AI's limitations in areas such as creativity, critical thinking, and emotional intelligence, aspects where human cognitive abilities still hold an edge.

The comparative analysis of essays written by psychology students and AI chatbots like Claude 2.1 and ChatGPT 4 has revealed distinct differences in creativity, depth of thought, and emotional expression. This underscores the unique contributions that human insight brings to the educational process, contributions that AI currently cannot replicate.

Despite these limitations, AI's role in augmenting the educational process cannot be understated. Its ability to handle routine tasks, provide instantaneous feedback, and offer a vast repository of information makes it an invaluable tool in an educational setting. This integration, however, necessitates a re-evaluation of educational methodologies and the development of new pedagogical strategies that balance AI's computational prowess with the nuanced understanding and emotional depth of human instructors.

Moreover, the emergence of roles such as prompt engineers, AI user facilitators, and AI facilitators reflects the growing complexity and interdependence of human-AI interactions in educational contexts. These roles highlight the necessity for educators and students alike to develop a deep understanding of AI capabilities and limitations, ensuring that AI tools are used effectively and ethically.

In conclusion, the future of education, particularly in psychology, lies in a synergistic relationship between human and artificial intelligence. This partnership promises to enrich learning experiences, foster innovation, and prepare students for a rapidly evolving technological landscape. Continuous research and adaptation in educational methodologies are essential to fully realize AI's potential in education, ensuring that it complements rather than supplants the human elements that are central to the learning process.

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A school that prepares for sustainability management: the case of the Palau model

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A school that prepares for sustainability management: the case of the Palau model

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Abstract. Humanity's transition to sustainable development requires society to have a culture of decision-making that takes into account the long-term perspective of interaction with complex systems that demonstrate a non-linear response to impacts. Modern school education does not teach to make such decisions, which may be one of the reasons why modern schooling is in crisis. To provide useful experience for real-life decision-making, the authors propose including interaction with simulation models in education. In this work, we talk about the experience of independently creating and using such a model in the educational process. The authors proposed a model that teaches how to find optimal ways of using fish stocks in several interconnected water areas. In honor of the experience of the Republic of Palau popularized by David Attenborough, this model is named Palau model. The dynamics of such a system are counterintuitive, where restrictions on fishing ultimately lead to an increase in fish catches. The work describes the logic behind the Palau model calculations and discusses its implementation using the R language that facilitates the study of its properties. In the 2021 pedagogical experiment, the model was implemented using Google Sheets for 10th and 11th-grade high school students. Despite the lack of experimental data, the experiment showed the admissibility of using such models in the real educational process. The authors consider the development and testing of similar educational tools to be promising.

1. Why should humanity move to a way of decision-making that ensures sustainable development?

Sustainable development is a way of effective interaction with the surrounding world today, which will not eliminate the possibility of such interaction in the future [1]. The social, ecological and economic foundations of sustainable development cannot be properly implemented without the creation of education system that will teach people to effectively improve these areas of life in the long term. In our opinion, education is a key link for all pillars of sustainable development and should be given special importance.

Ensuring humanity's transition to sustainable development requires changes in the decision-making algorithms concerning the interaction of people and their groups with the environment. The way humanity has been making decisions throughout its history is not conducive to the sustainability transition. Is it possible to hope for a change over time? If so, what do we need to do to make this change happen?

In democratic countries, the decision-making mechanism of the authorities is heavily influenced by the mood of the voters. This influence often leads to the prioritization of "quick fixes" over sustainable solutions. In such cases, voters tend to support actions that will improve their immediate conditions, rather than those that address long-term sustainability. Authoritarian countries are focused on ensuring the stability of the regime at the moment before the priority of ensuring the stability of relations with the environment in the long term. In such conditions, hopes for coordinated changes in the course of action are unrealistic.

So, how can we help society make decisions that are adequate to achieve a sustainable state? Our solution is to create conditions under which citizens gain experience in making long-term decisions. Where can such experience come from? First of all, it should be provided by the education system. We believe that professionals planning society's transition to sustainable development should contribute to the restructuring of school education. Students should learn problem-solving skills that can be scaled and developed to contribute to humanity's transition to a sustainable state.

A study of the history of such ideas development in the scientific and pedagogical literature would require separate work. Therefore, it is important to note that the described requirements for the simulation model developed and tested by the article's authors are based not on the ideas expressed in the literature, but on our pedagogical experience.

2. Education system crisis and its disconnection from real life

We believe that the modern school system in Ukraine and many other countries is currently facing a major crisis. The COVID-19 pandemic has posed a significant challenge for the education system as it has shifted many students from full-time to distance learning. The full-scale invasion of the Russian Federation has become a much more powerful destructive factor, causing many students to become internal and external migrants and leading to the closure or destruction of many educational institutions. Strangely enough, in many cases, these processes have given new meaning to the continuation of the educational process: the main thing is that it continues despite the terrible obstacles. However, assessments of the effectiveness of education, such as the Program for International Student Assessment (PISA) [2], show that its quality is declining.

Despite the current problems, it should be noted that the substantive crisis in Ukrainian education began much earlier, even before the COVID-19 pandemic. Students were losing their understanding of why they should learn, and teachers were losing their understanding of why they should teach. We believe this is a consequence of the disconnect between typical school activities and the requirements that life has placed on a school graduate.

Success in life is a culmination of productive interactions between an individual and their surrounding systems, which include oneself, potential partners, social structures, organizations, working tasks, and the environment. To equip students with the necessary skills to tackle important life tasks, modern schools rely on traditional educational approaches such as examples, tests, questions, and occasionally "creative" works within a certain canon (table 1).

School tasks and life challenges are very different. School tasks and life challenges are two distinct domains. It is possible that individuals who excel in both areas possess a natural aptitude for problem-solving, and did not acquire it solely through academic preparation. Some people may be successful in solving problems in a certain area, but not in others, because they have not been trained in systems thinking...

3. Changing the nature of learning approaches

The organization of learning activities at school is largely explained by historical reasons. Comenius's classroom lesson system proved to be surprisingly effective for its time. At the same time, many features that ensured its success are now a thing of the past. Teachers are no longer the only source of knowledge and learning materials are no longer limited to printed books and lost their emotional value. Today's students are developing in a much more complex environment that offers a variety of alternative sources of information.

Table 1. Features of traditional learning tasks and target systems in real life.

Feature	Traditional learning	Target system in life
Complexity: the number of causal chains that determine system behavior	Simple: for understanding, it is enough to trace a single cause-and-effect chain	Complex: behavior is determined by the interaction of several causal chains
Correspondence of the causes that determine the system behavior to the branches of science	One-field: issues related to one academic subject are considered	Interdisciplinary, not limited by our usual division of sciences and academic subjects
The completeness of information about the important system properties	Full information (which is usually given in the terms of the assignment)	Incomplete information; we have to make assumptions about important aspects
Determinism: whether the initial conditions completely determine the outcome	Deterministic: the conditions of the problem uniquely determine its only correct answer	Non-deterministic (stochastic): conditions determine the probability distribution of possible outcomes
Dependence of the system's response on the nature of the impact on it	Linear: the change in the system is proportional to the effect on it (there will be more water in the pool if more water is poured into it)	Non-linear, often threshold or paradoxical, counterintuitive: the response of the system can even be oppositely directed relative to the influence on it
Emotional involvement in solving the task	Relative detachment: tasks are performed to obtain external approval or reinforce the self-image	Life involvement: the success of solving life problems is the success of the person

For instance, a student who is not interested in traditional classroom learning may be more engaged in interactive computer games. Finding solutions to problems posed by such games also involves effective interaction with classmates and other people.

In our opinion, one of the best solutions for the effective restructuring of school lessons is the widespread introduction of individual and group work with interactive digital models into school activities. These models' tasks should be closer to the properties of the target systems in life (table 1), rather than traditional learning tasks.

To ensure such an evolutionary change, certain point changes should be selected that can become positive examples of future-oriented changes. Let's look at one such example.

4. Two types of approaches: traditional and modeling

Let's look at the described difference with an example, starting with a traditional learning task.

Suppose a modern trawler can catch and process 120 tons of fish per day. Then, will one such ship suffice to meet the annual consumption of 20 kilograms of sea fish per capita for the entire population of Ukraine (which is estimated at 40 million)?

The biggest drawback of this task is its reliance on linear logic, where the response to human actions is always the same: more fishing – more catch. But we live in a world that works according to other laws, and often catching more means getting less! This example is not the worst. It is clear how the task is related to life (not a bad option in terms of engagement). The task has so-called "Interdisciplinary connections" – going beyond one field. However, it is still a simple deterministic linear system that includes all the information necessary for the solution. If a trawler catches 120 tons per day, it will catch 3,600 tons in a month...

This logic leads to a planetary crisis caused by the depletion of fish stocks. In 'A Life on Our Planet' [3], David Attenborough highlights the experience of the Republic of Palau, where fishing is one of the main industries. A complete ban on fishing in certain waters of this island nation has increased the total fish catch. Fish reproduce in protected areas, settle in the surrounding waters and, ensure a stable fishery. Let's discuss the following task.

There are several bays along the perimeter of the island where commercial fish live. The number of fish is affected by various factors such as:

- *fish reproduction, which is dependent on its population size;*
- *environmental restrictions in bays (availability of food, etc.);*
- *movement between bays (fish migrate to neighboring bays if there is a free environment there);*
- *human fishing activities.*

How exactly to fish on such an island? Fishing can be allowed in all bays or only in some of them. If fishing is allowed, it can be carried out in different parts of the fish stocks. The question is which option would result in the largest annual catch in the long run.

The system of replenishing and utilizing fish stocks is complex and depends on the interaction of reproduction, dispersal, and catch. It requires a multidisciplinary description, and many of its characteristics are only approximately estimated. Its long-term future also requires further research.

The dynamics of such a system are paradoxical and counterintuitive: fishing restrictions ultimately lead to an increase in fish catch, which can be difficult to understand.

Due to the counterintuitive behavior of such systems, people who are not trained to interact with them constantly make mistakes that are much more dangerous than mistakes in solving linear school examples.

What could be easier than using not tasks like an example about a trawler at school, but tasks like fishing in Palau... But how to build such tasks, how to work with them? Such work requires a change in the very nature of educational activity!

Let's say we have created a simulation model that visualizes the dynamics of fish reproduction, settlement, and catch in a region. This is a program that can work both online and offline on a computer, tablet, or smartphone. This model can be used in demonstration, interactive, and research modes.

Let's define a water area in the model that is divided into sites. Fish can live and reproduce in these sites if there are sufficient resources; they can also move to neighboring sites. Reproduction depends on the number of sires and available resources. Fish are caught by fishing vessels; the catch depends on the number of fish in the site. The user sets the number of fishing vessels and sites with fishing. The task is to maximize the catch in the long run.

In the demonstration mode, the teacher can show how to interact with the model (but you can also allow the student to figure out how it works interactively).

In the interactive mode, the student sets a certain solution to a learning problem. The model then calculates all the consequences of this solution. The student receives the result of the model's work, along with the dynamics of fish production from the model, and then attempts to improve the previous solution. The work should resemble a game with excitement maintained on the principles of both a puzzle (we know it can be done, but how?) and competition (who found the best solution – you or someone else?).

The complexity of a model can be associated with an increase in the number of cause-and-effect chains that affect the outcome:

- homogeneity and heterogeneity of available resources across different sites;
- the impact of random fluctuations like hurricanes on the model's behavior;
- changing resource consumption, size, and fecundity of fish with age over time;
- different fishing methods, with different degrees of success for fish of different ages;
- economics: changes in the price of fish depending on the catch and accounting for fishing costs;
- differences in commercial fish species (less valuable planktonic fish and more valuable predators that feed on them), etc.

5. Comparison of the work nature with tasks of different types

The interactive use of models has the benefits of both traditional learning and learning through daily life (table 2).

The "higher" level of model use – the research mode – should be associated with the possibility of changing the model itself. Students will then fully understand the model when they can "disassemble" it and "reassemble" it.

The software implementation of a model is essentially a practical embodiment of a conceptual model, which can be defined as a set of input parameters (initial conditions and the solution provided by the user), along with calculated parameters and the relationships between them (formulas and conditions for their application). This set ensures the calculation of the final results. The research mode involves the analysis of exactly which relationships between parameters determine the characteristic behavior of the system. How to ensure model transparency for such analysis? Two options are possible:

(i) the same software implementation of the model can be used for demonstration, interactive, and research modes – in this case, the user has access to the "insides";

(ii) the research mode is provided by a different implementation, for example, an interactive model made in spreadsheets (no visualization, but the calculation mechanism is clearly understood).

6. How can modeling tasks be effectively implemented in schools?

Ecology, as a science of interactions, provides excellent opportunities for modeling target systems that students will encounter in real life.

To overcome the crisis of school education with the help of simulation, it is necessary to define the desired result, and then identify the steps required to achieve it. For us, the desired state of a school is one in which students are successfully taught to solve problems that are important to their fate. Graduates of this school can manage complex non-deterministic systems in conditions of information scarcity, are not afraid of the counterintuitive reaction of such systems, and know how to learn from the process. Students of such a school understand why they are studying, and teachers know how to teach such (!) students to solve such (!) problems... Achieving this ideal requires significant resources and time investment, but it is possible through the widespread use of simulation models.

Table 2. Comparison of different ways of learning.

	Traditional learning tasks	Interactive work with models	Adapting to the environment in the course of life
Task setting	The task is set by the teacher, determining the next stage of complexity of the educational work	The teacher directs the student to work with the model; the further result of the work is determined by the interaction with the model	The task is set by the process of human interaction with the environment (with his/her life)
Tasks sequence	Usually a predetermined sequence of tasks proposed by the teacher	The sequence of tasks can be ensured by gradually complicating the models	Often there is no sequence; we are surrounded by unpredictable tasks of varying complexity
Necessary foundation	Usually textual explanations: teacher's narration or textbook; own student's experience in solving previous problems is also important	Use of a model in demonstration mode or own practice with interactive use of simpler models	Sometimes it is known how others solved similar problems/learning during previous experiences or during the solution itself
Motivation	The student solves problems to fulfill the teacher's instructions; motivation is mostly external	The student follows the teacher's instructions and is stimulated by the excitement of "fighting" the model or competing with others	The person is involved in the process; sometimes evading the decision for fear of making a mistake
Evidence of success	Often, the student cannot distinguish between correct and incorrect solutions and must wait for the final grade	Success or failure of the model is quickly apparent; one can learn from the process	In most cases, the success or failure of the effort is obvious; one makes trials and errors and learns through this process
Repeated solution attempts when failing	Failed tasks can sometimes be attempted again	In case of failure, work with the model can be repeated until victory, taking into account the experience gained	Fixing a failed solution is often difficult or impossible
Result evaluation	The result of the work is evaluated by the teacher according to his/her criteria	Both the model itself and the teacher can evaluate the solution	Life itself evaluates a person's success

An intermediate step may be to create and use a set of models that can support a specific section of existing educational courses or even a new small course. What kind of school courses might we be talking about? In Ukraine, such courses are the following:

- integrated courses in biology and geography;
- a special course on modeling ecological systems;
- integrated natural science courses, including the course "Natural Sciences. Past, Present and Possible Future of Humanity and the Biosphere" [4], etc.

7. Description of the Conceptual Palau model

The implementation of simulation modelling in the school education system should start with relatively simple models. One of these models, created personally by the authors of this article, is described below.

Let's consider a territory consisting of several linearly connected areas (each bordering the other two); assume that they are connected in a ring. To visualize such an arrangement, let's take the example of an island with coastal waters divided between six bays. Each "bay" has a certain number of fish. If the number of fish is less than the carrying capacity of the environment (the number that can exist in this area), they can reproduce and increase their number. If neighboring areas are filled to different proportions of their capacity, a certain number of fish move from the more filled area to the less filled.

The fish stocks of this "island" can be exploited. Fishing can take place in certain areas. The pattern of use (the relative location of the areas where fishing is carried out) and the intensity of fishing (the proportion of fish stocks that are removed at each step of the model) are determined by the user.

The main task that can be solved with this model is maximizing fish catch in the long run.

The described model can be characterized by the following main parameters:

- n is the number of areas corresponding to the bays along the island's perimeter that form a ring; in this particular example $n = 6$;
- K is the habitat capacity (Verhulst parameter) – the number of fish for which there is enough resource on the site; the capacity of different sites may be different or, as in the examples considered, the same;
- r is biotic potential (Malthus' parameter) – a measure of the fish stock's ability to reproduce; the proportion by which the number of fish increases for each step of the model if they do not feel the limitation of the number of resources they need;
- m (mobility) is a measure of fish ability to move between neighboring areas; movement should be calculated based on the m measure and the difference between the occupancy of fish in neighboring areas;
- u (use) – the intensity of use of the areas where fishing is carried out, the share of fish stocks that are removed at each step of the model;
- *pattern* – relative location of areas where fishing takes place.

How to characterize the pattern of site use is not an easy question. In the case of six sites with the same environmental capacity, we can specify 13 options for the relative location of protected and exploited areas.

In general, the pattern of use of 6 identical plots can be explained by the diagram (figure 1).

The scheme (figure 1 A) shows 6 sites with possible transitions between them.

The number of fish in the i-th site (N^i), as schematically shown for site #1, increases proportionally to r, but this growth is limited by the capacity of the environment K according

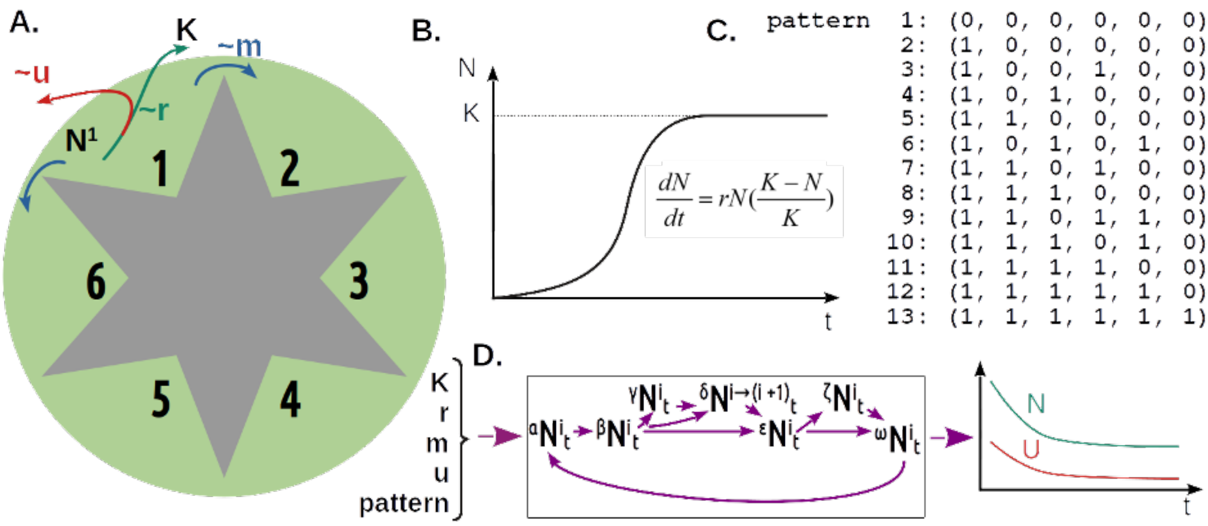

Figure 1. Scheme of the Palau model.

to the logistic model (shown next to it, figure 1 B). A decrease in the fish amount reduces the catch (if its pattern involves the use of the corresponding site); this catch is proportional to u.

If K is the same at all 6 sites, there are 13 different patterns of their use (figure 1 C): *pattern* 2 (one site is exploited) equally corresponds to cases where any of the 6 sites are exploited (because they are the same); *pattern* 1 corresponds to the absence of exploitation, and *pattern* 13 corresponds to the simultaneous use of all sites.

The main logic of the model is presented visually (figure 1 D). The set of input parameters determines the main calculations. At each cycle of the model work, the number of fish at each site is recalculated – from alpha numbers, ${}^{\alpha}_{t}N^{i}$, to omega numbers, ${}^{\omega}_{t}N^{i}$. The index i in these notations corresponds to the site sequence number, and t to the cycle of the model work. The output is presented as dynamics of fish amounts at each site (and the dynamics of the total number, N), as well as the dynamics of catch (total catch, U).

As will be explained below, the meaning of the stages of population recalculation is as follows:

- alpha numbers (${}^{\alpha}_{t}N^{i}$), the initial numbers of fish at each cycle;
- beta number (${}^{\beta}_{t}N^{i}$), the number of fish after reproduction;
- gamma number (${}^{\gamma}_{t}N^{i}$), the number of fish that would be achieved in case of their complete redistribution between sites i and $i+1$;
- delta numbers (${}^{\delta}_{t}N^{i\to(i+1)}$), the number of fish moving from site i to site $i+1$;
- epsilon numbers (${}^{\epsilon}_{t}N^{i}$), the number of fish in the sites after the relocation;
- zeta numbers (${}^{\zeta}_{t}N^{i}$), the number of fish caught from the site;
- omega numbers (${}^{\omega}_{t}N^{i}$), the final number of fish at each cycle (after capture).

8. Properties of the Palau model

We developed a system and created the Palau model in the R environment to study its properties. The R language script, which includes detailed explanations, is freely available on the Internet [5]. We implemented a variant with six identical sections that considers the combination of patterns of site use (the relative location of protected and fished bays) and fishing intensity in those areas open to exploitation, given a rate of reproduction (r) and mobility (m). The model calculates the dynamics of fish stocks and catches during 200 cycles (conditional years) for each selected combination of parameters. During this time, the system enters a stationary state, where fish stocks and catches become stable. The success of the exploitation of reserves is determined by the average total catch (for all exploited areas) during the last 20 cycles (from 181 to 200 cycles of model operation). The results obtained from the model can be viewed both numerically and on a 3D diagram (figure 2).

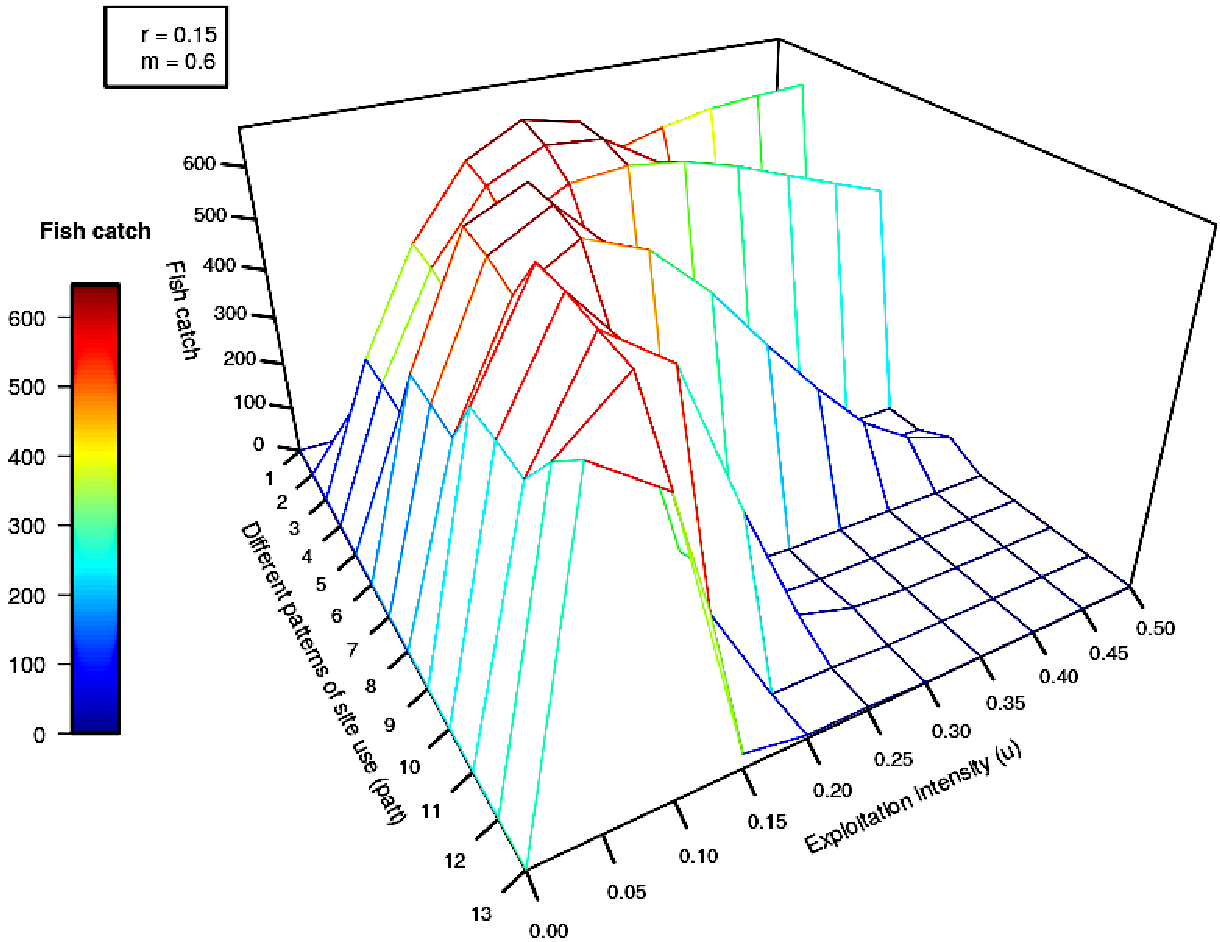

Figure 2. Results of visualizing the average catches for different patterns of area use and levels of exploitation, for a chosen value of fish reproduction and migration rates. The X-axis reflects the different degree of exploitation of the area – from a complete prohibition of fishing to catching half of the fish present in the area. The Y-axis shows catch volumes (for ease of understanding, the numerical values correspond to the color scale shown on the side). The Z-axis shows the beginning of each of the 13 patterns of site exploitation discussed.

In figure 2 shows several characteristic features of the model. In general, the model shows a more efficient use of fish stocks in the presence of protected areas, particularly in the case of relatively intensive fishing with exploitation. An increase in catch in response to increased exploitation occurs only when protected areas surround exploited areas, under the condition of high mobility of fish stocks. Even the presence of individual protected areas does not protect fish stocks from depletion in case of high intensity of exploitation. This is a consequence of the cessation of the reproduction of fish in case of a decrease in their number below the critical limit.

The optimal operating method depends on the interaction of several factors and their interaction is relatively unpredictable. To optimize the operating mode of a system, it's necessary to experiment with it and observe how it reacts to different settings.

The model we created in R is similar to real life in several ways. We believe that non-"survey" models, like the one we built, are more effective when working with schoolchildren. It is better to start with models that respond dynamically after a specific mode of operation is selected. Schoolchildren can study the properties of such a system based on the results of a series of attempts. "Review" models can be useful at a later stage to integrate the acquired experience.

9. Testing the concept in the school learning process

In 2021, we conducted a pedagogical experiment to test a new model in the educational process. We analyzed the work of 85 students in the 10th and 11th grades of the Public institution "Kharkiv University Lyceum of Kharkiv City Council Kharkiv region". This educational institution started to implement the experimental integrated course of natural sciences "Past, Present and Possible Future of Humanity" according to the program [4].

The lessons were held in two blocks: "A. Scientific Method and Natural Sciences" for 10th graders and "M. Agriculture as a Source of Substances for Humanity" for 11th graders. Both blocks used mixed types of lessons that involved interactive teaching approaches. Two different methods were used for teaching – traditional and interactive. Students taught in alternative ways took a common test after the lesson. The test was related to the topic covered but did not contain elements that were directly related to the material considered in the traditional or interactive form.

The students in each class were divided into two groups randomly by picking a candy of one of two colors from an opaque bag. The students who were taught within the traditional approach were assigned to read the learning materials in the form of text with bar charts, illustrations, and videos by following the link [6]. On the other hand, students who worked with the interactive model were given links to instructions on how to use the model [7] and how to implement the model using Google Sheets.

The knowledge gained in the course of studying this topic was tested using a test using Google Forms. The test included reproductive, competency, and general erudition tasks. Statistical analysis of the results was done using non-parametric Mann-Whitney and ANOVA comparisons.

The analysis of the final test results revealed that 11th-grade students performed better than 10th-grade students. However, no significant difference was found in the distribution of final test results between the traditional and interactive learning methods. Nevertheless, a statistically insignificant trend was observed, indicating that the use of interactive learning methods led to a slight decrease in academic achievement of less prepared students, while more prepared students showed a certain improvement.

Unfortunately, the model testing was interrupted due to the Russian Federation's attack on the Kharkiv region, which resulted in the disruption of educational institutions' work. Despite this, it was possible to establish that the use of simulation models instead of traditional teaching methods did not negatively affect the students' performance but is promising for future improvements. Therefore, it can be concluded that the use of simulation models in the educational process is acceptable.

10. Prospects for further research

Even though the experimental study of the Palau Model was disrupted by intense hostilities resulting from the aggression of the Russian Federation, the authors believe that it is extremely important to create, test, and implement similar models in the educational process. However, the application of the approach described in this paper is constrained not only by technical problems. To integrate promising forms of education into the educational process, it is necessary to restructure it. This restructuring should form the basis of ensuring sustainable development, starting from the school desk.

Acknowledgments

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The use of digital technologies in education in the context of sustainable development of society

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Abstract. One of Ukraine's Sustainable Development Goals is to ensure inclusive and equitable quality education and to promote lifelong learning opportunities for all citizens. Therefore, it is important to develop the professional skills and pedagogical competence of teachers to prepare future generations to achieve the Sustainable Development Goals through education. In particular, through the digitalization of education. The purpose of this article is to highlight the state of use of digital technologies and innovative approaches by teachers of Kryvyi Rih district in the context of blended learning in the context of sustainable development of society. The problems of development and use of video materials and interactive tools, virtual simulations, workshops and laboratories in teaching are considered. The issue of using game technologies for learning is highlighted. The use of platforms for collaboration and exchange of views between students and the use of e-learning systems is analysed.

1. Introduction

Today, digitalization is seen as an important driver of socio-economic development [1, 2]. The educational system, determining the social profile of the country's future, plays an important role in society. In particular, as a factor in eliminating inequality among citizens. One of the Sustainable Development Goals of Ukraine, as stated in the Presidential Decree [3], is to ensure inclusive and equitable quality education and to promote lifelong learning opportunities for all citizens [4].

Preparing generations to meet the Sustainable Development Goals is a major challenge. The use of cloud technologies [5–11], augmented reality [12–24], the development of tools for collecting and analyzing Big Data, 3D printing, etc. are changing both various sectors of the economy and society as a whole. This requires the training of a teacher who is motivated and able to participate in the creation of a new school based on the widespread use of digital technologies, cooperation and mutual understanding between all participants in the educational process.

Therefore, a modern teacher should be focused on professional and personal growth throughout his or her teaching career. Education for sustainable development is lifelong and includes all levels and categories of education and training. This includes formal education, including secondary and higher education, as well as retraining and re-qualification. In non-formal education, self-education, including for people of retirement age, is the mainstay.

In the context of the unstable security situation in Ukraine, a significant number of higher and secondary education institutions have been forced to switch to online or blended learning. This has become a serious challenge for many participants in the educational process. Many studies show significant educational losses caused by the inability to fully conduct classes. The difficulties of transitioning to online learning are especially noted by future teachers who are undergoing internships in educational institutions. This has revealed serious shortcomings in the pedagogical integration of ICTs, raising awareness of the need to develop digital competencies for each of the participants in the educational process.

The appropriate use of digital technologies in education will help make the learning process effective, accessible and motivating for students. It will help to ensure that the Sustainable Development Goals are met.

2. Theoretical background

Sustainable development is development that meets the requirements of the present without compromising the ability of future generations to meet their own needs. Fedulova [25] characterizes the global trends in the development and implementation of digital technologies to achieve the goals of sustainable development in the context of digitalization of the economy and society, and identifies key tasks in this area for Ukrainian science and public policy. The author identifies the following trends: 1) the complex impact of Industry 4.0 technologies on the achievement of the Sustainable Development Goals; 2) digital technologies as a driver of a new stage of sustainable development and opening of new markets, which concerns the activities of large corporations; 3) the intensification of international organizations in the transfer of digitalization policy.

García-Hernández et al. [26] note that adequate use of ICT is necessary to promote educational practices that contribute to sustainable development. The systematization of research in this area is seen as an opportunity to contribute to existing theories and practices related to the use of ICT and the development of the Sustainable Development Goals. According to the challenges, the authors identify innovative proposals that can be used to address sustainable development issues. In particular, the development of sustainable technological tools can be ensured through the creation of virtual tools or courses for quality education, and e-learning strategies need to be improved to ensure equitable and quality education.

Jeong and González-Gómez [27] consider mathematics education as a cornerstone for sustainable development. However, the problems of sustainable development are related to the typical issues of ecology and economy in the educational sphere. The authors note that, under the influence of modern ICT, changes in pedagogy lead to significant contradictions in teaching/learning mathematics. This study attempts to classify and investigate the criteria of mathematics education using the method of multi-criteria decision analysis/testing laboratory and fuzzy decision evaluation in the context of a flipped e-learning system.

Hilty and Huber [28] investigate the motivation of ICT students to study specific topics in the field of sustainable development.

Al-Rahmi et al. [29] highlight the problems of usng ICT for sustainable development of education. The authors analyze the factors that influence the intention to use ICT in education and their satisfaction with this use.

Serhiienko [30] defines that the tasks of education for sustainable development are reorientation of existing curricula towards social, economic, environmental knowledge and perspectives; formation of experience and values necessary for sustainable development; training of personnel in the interests of transition to sustainable development and further development of education for sustainable development.

The problems of digitalization of education are reflected in the work by Dziabenko et al. [31]. Among the tools of digital technologies, the authors distinguish tools for communication, collaboration, content creation, work organization, search, video and audio, and mobile applications. Educational trends include, in particular, practice-oriented learning, competence development, personalization, STEAM education, and entrepreneurship development. The authors of the study note that the most popular pedagogical technologies are research-based learning through the use of ICT, blended learning, maker education, formative assessment, integrated learning and inclusive education technologies.

Kartashova et al. highlight the technology of digital twins for blended learning in educational institutions [32]. This will provide free access to educational resources and networking for students.

Kuzminska et al. [33] study the problems of forming digital competence of students and teachers in Ukraine. In particular, measurement, analysis, and development prospects.

Mintii [34] notes that today, blended learning is characterized by studies that consider practical experience of implementation. The leading approaches to the organization of blended learning are highlighted: by the method of combination, by ICT tools, by appropriate pedagogical technologies.

The studies discussed above actualize the issue of forming professional skills and pedagogical competence of teachers to ensure the Sustainable Development Goals of society through education. There is a lack of research that would systematize innovative proposals that contribute to solving the problems of sustainable development of education. This is especially true for inclusive education and education in an unstable security situation.

3. Methodology

During 2021-2023, we monitored the use of digital technologies by mathematics and computer science teachers during their internships in educational institutions of the Kryvyi Rih district in a blended learning environment. We also conducted a survey on the use of online tools by math teachers during their professional development courses. Almost ninety teachers answered the questionnaire about the use of digital technologies during this period.

As part of the teacher training courses, we invited experienced math teachers to share their practice of using digital technologies in blended learning. At the same time, invited guests and experts took part in discussions, answered questions from students to expand their knowledge and improve their skills in using online tools.

The purpose of this article is to highlight the state of use of digital technologies and innovative approaches by teachers of Kryvyi Rih district in the context of blended learning in the context of sustainable development of society.

4. Results

Blended learning involves traditional classroom training with online learning; online learning with the possibility of contact with a teacher; simulation with structured courses; on-the-job training with some informal classes; management coaching with distance learning activities [35]. In Ukraine, various blended learning models are currently being implemented that allow for the most appropriate combination of group learning with independent study, small group work, technology integration, and a combination of face-to-face, synchronous, and asynchronous distance learning. It is important to ensure personalization of learning, take into account the individual needs of each participant in the learning process, and promote their high expectations of the learning process. The organization of blended learning requires careful selection of learning content, the use of modern technologies, and the creation of an effective learning environment.

4.1. Use of video materials and interactive tools

To provide asynchronous learning, teachers/lecturers widely use video lessons created by themselves or selected from the Internet. By creating video lessons, they can demonstrate appropriate teaching methods and solving typical problems. Among the most popular platforms and tools that are most often used, YouTube [36] is the most popular. 100 % of respondents use the lessons they find that are useful. 37 persons (43.0 %) said that they periodically create or upload their own lessons to YouTube.

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This is due to the possibility of providing easy access to video lessons for students, using the platform's video editor to add explanations, animations, and other elements. Very often, teachers/lecturers record live online lessons in Zoom (42 persons, 48.8 %), Google Meet (12 persons, 14 %)), or Microsoft Teams, which can be used for later viewing. In this case, they use the functions of the on-screen part and annotations to explain various concepts in detail. Teachers who do not record lessons in a blended learning environment mentioned the following reasons: fewer students participate in the lesson if the recording is made public later. Some students are embarrassed to know that their answers are being recorded and will be made public, even within the classroom. Recording impairs access to the network for some students, especially in rural areas, areas with significant destruction due to war, etc.

For future teachers to be able to freely create video lessons that are understandable to students, they need to prepare them in advance by completing similar tasks.

Some students noted that they used the Khan Academy platform (17 persons, 19.7 %), which has a built-in video editor and other tools, to create video lessons and study subjects. Teachers often used the Geogebra [37] dynamic math system to create video lessons, including interactive demonstrations and graphs (32 persons, 37.2 %). The teachers interviewed noted that Camtasia and Screencast-O-Matic, although they have free versions, were not used to record the screen and edit the video, add tips, animations, and sound.

Teachers widely use virtual whiteboards, such as Jamboard (63.1 %), Clever Maths (27.4 %), and Zoom Whiteboard (79.8 %), to prepare and deliver online lessons (see figure 1). Some teachers reported positive experiences with Miro (6.0 %), One Note (9.5 %) and Idroo (20.2 %) virtual whiteboards (figure 1). As practice has shown, a particularly high learning effect is achieved if participants in the learning process write synchronously on the board using a graphic tablet, special styluses, etc. Even if there is a multimedia whiteboard in the classroom, it is better to use virtual whiteboard software to ensure online collaboration. Virtual whiteboards in education can be used to simplify teaching, make explanations more accessible, and engage students in collaboration by providing different levels of access. It is convenient to use a virtual whiteboard to create concept maps or diagrams to visualize the connections between different topics.

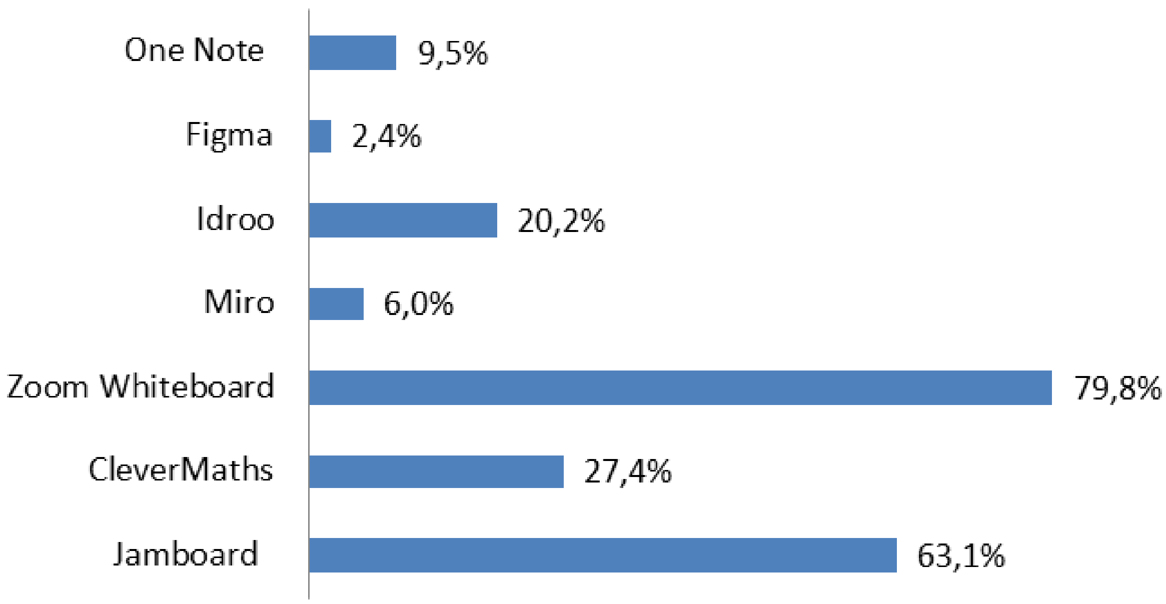

Figure 1. Statistics on the use of virtual whiteboards by math teachers in blended learning.

Padlet, an online collaboration tool, is widely used (40.7 %). Using Padlet, students create, add and discuss various tasks. The use of these interactive tools can make it easier for students to learn new things, giving them the opportunity to master the materials more efficiently.

From our own experience of training future mathematics teachers, we can note that an increase in the level of methodological competence can be achieved if online lessons are developed by a group of students using one textbook. Then students, discussing their own lessons with colleagues, will realize the importance of ensuring continuity, implementing intra- and interdisciplinary connections. The developed lessons, along with other selected visualizations, were placed in an e-learning course on the Moodle platform.

4.2. Use of virtual simulations, workshops and laboratories

Teaching mathematics in the context of sustainable development of society is relevant in the context of STEM education, successful mastery of future IT specialties, etc. [38–40] Simulations [41–44] and virtual laboratories [45, 46] provide students with the opportunity to experiment, learn, and visualize natural and mathematical concepts. Such tools are especially useful when implementing STEM approaches in education. Among the popular platforms, we note PhET Interactive Simulations and GoLab (Global Online Science Labs for Inquiry Learning), which have an interactive and intuitive interface and provide a large number of free simulations in physics, chemistry, biology and mathematics, including game elements. The study considers the scientific and theoretical underpinnings of immersive technologies in mathematics teaching, as well as methods for using the AR-Book application [47].

Using these platforms, you can personalize the educational trajectory of each student. Participants in the educational process will choose a convenient time and pace for studying the material.

Before using a particular simulation, the teacher/educator should establish the purpose of the application, using leading questions to encourage students to think critically about it. Körtesi et al. [48] focus on learning and teaching mathematics and analyze the role and usefulness of ICT tools in education, such as computer algebra systems and dynamic geometry systems in the implementation of active and innovative teaching methodologies related to sustainable STEAM education.

Among the specialized programs and tools for teaching mathematics, Ukrainian teachers most often use the visual and interactive platform GeoGebra (32 persons, 37.2 %), specialized in geometry, algebra, trigonometry, and calculus, to study specific mathematical topics. Geogebra has not only interactive geometric object designers, but also virtual laboratories for learning algebra, geometry, statistics, and other areas of mathematics. A much smaller share uses Wolfram Mathematica (9 persons, 10.5 %), GRAN educational and methodological complex (12 persons, 14.0 %) and SageMath (6 persons, 7.0 %). Desmos is widely used by math teachers in their teaching practice (41 people, 47.7 %). The results of the survey are presented (figure 2).

4.3. Game technologies for learning

Gaming platforms are a convenient tool for creating educational games [49] aimed at consolidating math knowledge. It is an effective way to engage students and make learning fun. Pertegal-Felices et al. [50] compare the impact of the Kahoot tool on the training of teachers and students of computer engineering for sustainable development of society. To ensure quality education, the authors make proposals for gamification using ICT to increase the likelihood of success and sustainability of educational institutions.

LearningApps as a multifunctional platform is used to create interactive exercises. It is very popular among domestic teachers/lecturers because it is easy to use, allows you to quickly create different types of exercises for active learning and testing the level of students. The WordWall application is similar to the interactive environment of LearningApps, but has more templates

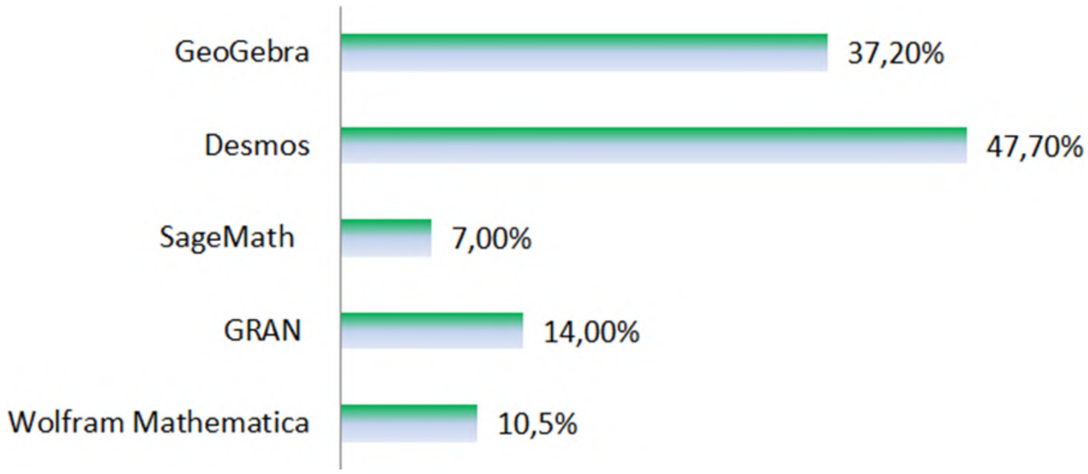

Figure 2. Statistics on the use of specialized programs and tools in teaching mathematics.

and functions. WordWall interactive exercises can be played on any web-based device, such as a computer, tablet, phone, or interactive whiteboard.

Kahoot allows you to create quizzes and question-and-answer games that can be used to test knowledge on various math topics and for formative assessment [51]. Quizizz is similar to Kahoot, allowing you to create question and answer games, but with a greater emphasis on the independent pace of students. It is advisable to combine surveys and the use of a smartphone with the online application Mentimeter.

53 teachers (61.6 %) reported using LearningApps exercises, 17 (19.8 %) – WordWall, 14 (16.3 %) – Kahoot, 6 teachers (7.0 %) – Mentimeter.

The following platforms are practically not used by Ukrainian teachers. Prodigy offers an online game that combines math tasks and adventure gameplay. The tool uses adaptive learning. Math Playground contains a variety of educational games, tasks, and puzzles to help students consolidate their math knowledge. Coolmath Games offers a large selection of math games that promote logical thinking and problem solving. Hooda Math offers a number of educational games focused on different sections of math.

Graphics and gamification can play a key role in creating an engaging and effective learning experience in education [52]. They help to create a stimulating environment in which learners are motivated to acquire new knowledge. This happens through the visualization of abstractions, gamification of tasks, and the use of games with a logical load. Appropriate gamification ensures personalization of learning by adapting content and tasks to the individual needs of students. Instant feedback is important, allowing students to see the results of their actions and improve their skills.

4.4. Using collaboration and idea sharing platforms

Among a number of free collaboration and idea-sharing platforms that can be used in education, Google Workspace and Microsoft Teams are popular among teachers/educators. Google Drive, Google Docs, Google Sheets, and other Google Workspace tools allow you to create, edit, and collaborate on documents and spreadsheets in real time. More than half of the teachers surveyed said that Google Meet is their preferred tool for online lessons (63 persons, 73.3 %).

Zoom is a video conferencing platform that allows teachers and students to communicate and conduct online lessons. In secondary education, teachers say they use the free version (71 persons, 82.6 %).

Platforms such as Slack, Discord, Trello, Asana allow students and teachers to work together, exchange ideas, create joint projects, and provide a user-friendly interface for real-time or asynchronous collaboration. However, these resources are not yet used by the teachers surveyed.

Organizing open discussions and interactions through online forums and discussion platforms can greatly enrich the learning process. For this purpose, it is advisable to create thematic forums, highlighting thematic sections or topics according to the sections of mathematics, so that learners can more easily find and discuss specific issues. It is important to promote the activity of participants by encouraging them to comment, add to and express their own opinions. It is advisable to establish a reward or rating system for active participants. The teacher should maintain an open dialog. In particular, to engage students in discussion by asking somewhat provocative questions, questions that are of interest, will stimulate their thinking and analysis. It is also worth considering delegating roles, such as moderator, to help organize and support discussions. Interactive online tools such as commenting, rating, or collapsing threads for easy navigation should be used. It is important to promote constructive communication and respect for the ideas of other participants.

Allow forum participants to add graphics, videos or other multimedia to better define their issues or illustrate solutions. It is advisable to promote collective problem-solving, stimulate discussion and exchange of different approaches to solving problems. The use of these strategies will facilitate active interaction and joint learning among participants through online forums and discussion platforms.

4.5. Use of e-learning systems

The models of blended learning that are currently used in the training of future teachers and in the professional development of existing teachers also differ due to the use of learning support systems such as Moodle, Google Classroom, and others. Open courses hosted on MOOC platforms are increasingly being used for training. The use of e-learning platforms can greatly facilitate the organization of materials, assignments and tests in training. Moodle is an open platform for creating e-courses. The advantages of using the platform and new opportunities are described by Mintii et al. [53]. Educators can download materials, create assignments and tests, and use forums for discussions. Although the e-learning system is recommended for higher education institutions and schools, we have not seen any reports in the questionnaire about the use of Moodle in secondary education institutions.

Most secondary education institutions use Google Classroom as an integrated part of Google Workspace, where teachers can create classes, add assignments, materials, and tests (71 persons, 82.6 %) .

Education departments and a large number of Kryvyi Rih schools cooperate with HUMAN, a Ukrainian ed-tech company that develops and implements products for the digitalization of the Ukrainian educational process, taking into account different levels of logistics and digital literacy in educational institutions. HUMAN provides comprehensive digitalization of educational institutions by consolidating tools for organizing the educational process, communication and analytics in a single system. As a result, the institution receives tools for full-time and distance learning, as well as transparent statistics of the educational process.

Canvas is an e-learning platform that allows you to create courses, assignments, tests, and communicate with students. According to respondents, Canvas is increasingly being used in educational institutions.

Some teachers said that they use the ability to create classes in GeoGebra as an interactive platform as an auxiliary tool. Teachers also mentioned creating courses using social media. The national educational platform Vseosvita (over 3.5 million registered users) provides teachers with a library of teaching materials, tools for designing lessons, tests, web quests, and the ability to keep electronic journals. 63 people (73.3 %) regularly use the materials of the Vseosvita educational platform, and 52 teachers (60.5 %) use the materials of the Na Urok educational platform.

When choosing a platform, it is important to take into account the needs and capabilities of students, as well as to determine which one best suits the teaching methods. Each of these platforms has its own advantages and opportunities for creating an effective learning environment. Therefore, future teachers should develop methodological competencies in the process of training to use these and potentially possible e-learning platforms in teaching students.

Tracking the progress of students and providing feedback through assessment systems should be an effective way to develop them and improve the quality of education. Let's consider strategies and tools that can be used for this purpose. It is advisable to use electronic platforms to create tasks and tests. For example, Google Forms, Moodle, or other learning management systems. Collecting data from such tasks can automate assessment and allow you to analyze the results. At the same time, use the functions of automated report generation, which can provide an overall picture of the progress of students. Such reports can include average scores, time spent on tasks, and other metrics. It is important to define clear evaluation criteria and use rubrics to assess different aspects of the work. This will allow students to better understand what is expected of them and provide specific feedback.

It is advisable to introduce different types of assessment to evaluate the quality of students' abilities and achievements, instead of limiting them to numerical grades. It is extremely important to take into account the individual characteristics of students when determining progress, to apply individualized tasks and assessments for each student. It is important to use reminder and task tracking systems to ensure that students are able to plan their time and complete their work on time. Thanks to these strategies and tools, it is possible not only to effectively track the progress of students, but also to provide them with constructive feedback for further development.

5. Conclusions

The successful use of digital technologies in education will ensure the achievement of the Sustainable Development Goals.

Blended learning, which combines traditional methods and digital technologies, can significantly improve the training of students by promoting the development of their skills and new teaching methods. This will contribute to the achievement of the Sustainable Development Goals. For the effective implementation of blended learning in training, it is advisable to integrate open online resources for the study of individual disciplines. Creating and completing interactive exercises and tasks is best organized through special platforms.

It is advisable to systematize virtual lectures and webinars, where experts can present new teaching methods or demonstrate the use of digital tools in teaching. It is important to ensure that students work practically with digital tools. It is necessary to use remote collaboration functions so that students can work together to solve tasks and solve problems. Creating online communities to discuss important topics, share ideas and resources will help build teamwork skills. In particular, through the use of forums, social networks or specialized platforms. To do this, you can provide students with feedback on their work through online platforms, taking into account both quantitative indicators and qualitative comments. This can apply to individual assignments or collective projects.

The use of adaptive technologies to individualize learning will help provide students with materials and tasks according to their needs and level of knowledge [54–56]. Blended learning allows students to acquire traditional knowledge while simultaneously becoming familiar with modern teaching methods and digital tools. It is also important to provide sufficient support and training for teachers to successfully implement these approaches. Maximizing the potential of artificial intelligence technologies in education and increasing public trust in them requires more detailed work.

In the future, in the context of ensuring the achievement of the Sustainable Development Goals, it is advisable to explore the prospects for realizing the potential of artificial intelligence technologies in education and increasing public trust in them.

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Ensuring sustainable development through the use of digital educational hubs for teaching civic education at school

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Abstract. The article highlights the practical experience of implementing digital educational hubs to support civic education (CE) to ensure sustainable development. The role of the digital educational hub as a modern tool of the digital educational environment was determined. The digital educational hub is a multi-functional digital educational environment with electronic resources, tools, technologies and educational materials where organisational and pedagogical conditions are created for the acquisition of knowledge, the development of students' competencies and the effective accumulation of intellectual potential, which contributes to professional development and the implementation of innovations in practice. The purpose of this article is to investigate how digital educational hubs support civic education at school, how teachers and school leaders can use the resources of the hubs, and how teachers in Ukraine and other countries are supported in using digital tools for teaching civic education subjects, which are important for the professional development of teachers, including the development of their digital skills. The experience of using digital educational hubs supporting CE at schools in Ukraine and European countries (Belgium, Canada, Netherlands) is described. The practical significance of the digital educational hub, as a component of the digital educational environment, is to support and implement innovations in school education that contribute to the development of the personality of a modern citizen, an active member of the digital society. The novelty of the research: online learning and remote forms of communication are the most popular in education today. For teaching civic education, there is a combination of active forms of learning with the use of digital means and resources, which are actively offered by digital educational hubs. Highlighting the best practices of such use is important both for the professional development of teachers and for the diversification and activation of students' civic education. The practical significance based on the experience of European countries, forms and approaches to the use of digital educational tools for teaching civic education has been identified. Methods of using digital hubs to support civic education at school need further research.

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1. Introduction

The development of science and technology is transforming, developing and improving old and creating new forms of organisation of human life, optimising and modernising them. Globalization and integration processes in modern society transform education and require the joint efforts of all educators, which leads to the renewal of approaches to the organization of education processes and, in turn, to the creation of a technologically saturated educational environment. International Telecommunication Union (ITU) and the United Nations Development Program (UNDP) adopted the Sustainable Development Goal (SDG) Digital Acceleration Agenda stating that "Digital technologies have a powerful multiplier effect, both positive and negative, and so it is vital to ensure that their use minimises any increase, entrenchment, or exacerbation of inequality, especially as very real gender, location, and broader digital and data divides exist. Intentionally inclusive approaches to digital development – which place people and the protection of human rights at the centre – are vital in ensuring that the risks of digital transformation are proactively addressed and that no one is left behind" [1]. An important factor that influenced the emergence of digital educational hubs as a centre for learning was not only strategies aimed at the digitisation of education and science in the world but also the circumstances in which the world educational community found itself due to a significant period of the COVID-19 quarantine, limited access to educational institutions and resources. According to the latest data of the international PISA study conducted in 2022 compared to 2018, mean performance fell by ten score points in reading and by almost 15 score points in mathematics, which is equivalent to three-quarters of a year's worth of learning. The decline in mathematics performance is three times greater than any previous consecutive change. One in four 15-year-olds is now considered a low performer in mathematics, reading, and science on average across OECD countries. This means they can struggle to do tasks such as using basic algorithms or interpreting simple texts. This trend is more characteristic of 18 OECD countries and economies, where more than 60% of 15-year-olds are falling behind [2].

This indicates the loss of stability and consistency in education systems and calls for finding effective solutions for equal access of students and teachers to educational services, among which digital technologies are considered important today. On the positive side, according to PISA 2022, on average in OECD countries, about three-quarters of students are confident in the use of various technologies, including learning management systems, school learning platforms and video communication applications [2]. At the same time according to UNESCO, 45% of national curricula frameworks of 100 countries did not refer to climate change; 40% of teachers are confident teaching cognitive dimensions but only 20% can explain well how to take action. This shows that the digital environment is important for students, which is the digital solution that ensures stability and access to learning and the involvement of students in the educational process [3]. It is obvious that today environmental education, as a harmonious part of civic education, contributes to pedagogical and social mobilisation strategies, which, based on the development of scientific, civic social and emotional competencies, strengthens the harmonious relations between children and youth in society and contributes to its sustainable development.

The Global Education 2030 Agenda UNESCO, as the United Nations specialised agency for education, is entrusted to lead and coordinate the Education 2030 Agenda, which is part of a global movement to eradicate poverty through 17 Sustainable Development Goals by 2030. Education, essential to achieve all of these goals, has a dedicated Goal 4, which aims to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" [4]. In this context, the Education 2030 Framework for Action guides the implementation of this ambitious goal and commitment [5].

One of the elements of the information and digital educational environment is the digital educational hub. The tools and the instruments of digital educational hubs can support any educational field, in particular the sphere of civic education (CE). The use of digital educational

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hubs aimed at specific topics is a new practice today. In education, this practice demonstrates the need for students and teachers to combine informational and educational resources to achieve pedagogical goals. Therefore, the study of the best educational experience of using digital educational hubs for the implementation of civic education is important and can be applied to the further development of digital education. Active citizens need political and civic foresight so that they can become constructive agents of change that can effectively contribute to building a new society of the future in harmony with nature. New technologies and science can help in this regard, as well as in more efficient use of resources. We will focus on modern digital educational hubs aimed at civic education and the formation of students' key civic competence.

2. Literature review

An important issue that is considered today by the educational community and many authors is the issue of education for sustainable development in the future. It is about the fact that education for a sustainable future is needed today more than ever before. Education for sustainable development needs to be strengthened given the current social economic and cultural context. It should be community-oriented, with knowledge and observance of natural laws, sociological imagination, and political insight to make it more suitable to meet the challenges of the 21st century [6]. Research is also devoted to what are the key problems in school, and higher and professional education from the perspective of sustainable development. Of great interest are the works on how it is possible to link sustainable development and learning, economic and moral interdependence of people and nature, management, assessment and evaluation of learning and globalisation [7]. Modern researchers claim that digital technologies today are an integral part of the educational process and provide significant benefits for teachers and students. They provide access to a significant amount of information and various bodies of knowledge and also facilitate direct communication, which is not limited in space and time. Scientists are also investigating how modern digital technologies, such as gamification, contribute to the development of skills and behaviour in the context of sustainable development [8]. Researchers emphasise the role of ICT, which they play in the human capacity development for sustainable development through the revision of competency-based education and training, in particular, it provides the opportunity to transition to sustainable economies, environments and societies by equipping persons with skills, knowledge and attitudes that motivates the adoption of sustainable lifestyles [9]. Ukrainian researchers examine contemporary problems in education related to sustainable development [10]. A group of scientists considers the issue of sustainable development through the prism of challenges and opportunities of sustainability in various domains [11].

The studies of Ukrainian scientists are dedicated to the justification of the theoretical and methodological foundations of digital humanistic pedagogy [12]. Scientists emphasise that modern educational processes in physical and virtual space, where ICT is used, are interconnected. The applied research is devoted to the problem of building an information and digital educational environment was carried out by a group of scientists, considering the design and use of a cloud-oriented educational environment [13–16]; technologies for using network resources in the educational process and synthetic learning environment [17]. A significant part of the studies is devoted to the development of information and communication/digital competence and modelling of the modern digital educational environment [18]. The experience of European countries related to the creation and use of the information and digital educational environment was also highlighted by Ukrainian researchers [19]. The peculiarities of the development of civic education in the digital educational environment are considered in the works of a group of scientists. The aspects, that are revealed are the following: the development of a computer-oriented educational environment for multicultural education of students in the countries of the European Union [20]; the use of digital learning tools in the professional activities of teachers to ensure sustainable development and democratisation of education in European countries [11,21].

Conceptual approaches to civic education are highlighted in the works of foreign authors [22]. According to Bîrzéa [22], civic education is aimed at fostering democratic citizenship; it is a set of practices and types of activities aimed at improving the preparation of youth and adults for active participation in democratic life through the realisation of their rights and responsibilities in society.

The issue of the creation, implementation and development of educational hubs as an innovative component of the educational environment in higher education institutions is highlighted by Bondar et al. [23]; the place of the hub in modelling processes of internationalisation of higher education was studied by Hrynkevich and Lutchyn [24]; problems of so-called hub schools and the role of educational hubs in the process of the future teachers training studied by Ozminska [25]; Fedulova defines the ICT component and features of innovation and technological hubs [26]; Knight write about international educational hubs and gave analysis of 10 education hubs in Asia, Africa and the Arab stated of the Persian Gulf region [27]; the problem of the school as a hub of educational and public space was investigated in the works [28, 29].

However, the issue of creating, using and developing digital educational hubs to support and promote civic education as an element of the information and digital learning environment has not been sufficiently researched.

3. Research results

In today's world, the free use of ICT plays an important role, which affects the acquisition of life skills, as well as the ability for effective cooperation and communication, which ensure the identification of a conscious and active citizenship position, as well as the implementation of the idea of digital citizenship. This is also reflected in the social component of the concept of sustainable development. Sustainable Development Goal (SDG) Digital Acceleration Agenda emphasise: "National digital transformation must be a whole-of-society effort – including leveraging the catalytic power of a whole-of-government approach, the digital talents and expertise of the private sector, and most crucially the credibility and expertise of civil society" [30].

The requirements of the modern digital society activate a renewed vision and innovative approaches to the organisation of human activity and education in particular. Innovations in the early 2000s became a new model of organising professional activities, in particular, co-working, collective offices, and hubs. The concept of a hub is widely used in the transport industry and the field of ICT, it namely means a centre of activity, attention or a central node of a network. In a broad sense, a modern hub is a centre where various resources are collected, cooperation and communication are carried out, experience is gained, training and education are held, and new ideas are accumulated, the implementation of which requires the involvement and unification of like-minded people, the use of resources and tools for the intellectual development. Activities carried out in today's technologically oriented world occur both in real and virtual space. According to the place of deployment, the hub can be: real, created based on a physical object (premises); virtual, which is placed online on special means (servers); combined, which combines the features of both real and virtual hubs. Thus, the hub is a network of partners and uses the capabilities of educational and scientific institutions, their resource base and scientific achievements, a kind of "innovative and technological hub" as "a new stage in the comprehensive use of opportunities and resources organisations, as well as companies to create joint products and provide services through the implementation of technology-dominant projects" [26]. N. Bondar, V. Gubenya, I. Pidtilok, and L. Sharan describe the hub activities in the working space and note that seminars and training, creative and musical meetings, the functioning of the library and cross-booking can be a part of the hub working processes [23]. Researcher J. Knight considers the hub to be an educational innovation in the field of higher education and identifies three types of hubs: student hub, hub talents and knowledge/innovation hub [27]. Hrynkevich and Lutchyn highlight the role of the educational hub as an innovative form of institutionalisation of rapprochement processes, and integration of national educational systems and their institutions into the global educational environment [24]. Based on the above-mentioned opinions, the digital educational hub can be characterised as a multi-functional component of the educational space with the use of ICT. It can be created to unite and concentrate digital educational resources, tools, and technologies. The hub should provide organisational and pedagogical conditions for the acquisition of knowledge, the formation and development of competencies, the implementation of cooperation and communication of participants in the educational process (students, teachers, heads of educational institutions, students, post-graduate and doctoral students, scientists, parents, public organisations and all interested persons). It is organised to support learning, the development of ideas and the exchange of experiences, acquiring connections with like-minded people and their associations. This contributes to the creation of innovations and their implementation in education, project activities, professional and personal self-development and self-improvement. Educational hubs are aimed at collaboration in any educational field, in particular, civic education. This educational space provides an opportunity to efficiently and quickly accumulate intellectual potential for solving urgent problems, and discussion of acute issues related to theoretical and practical aspects of civic education.

Sustainable Development Goal (SDG) Digital Acceleration Agenda (International Telecommunication Union (ITU) and the United Nations Development Program (UNDP) UNICEF) showcase 34 digital solutions, two for each SDG, highlighting the power and potential of digital. There are Learning Passport (mobile online and offline learning platform) and Atingi (online learning platform)/ Digital solutions for the training of teachers for the 4th SDG Goal. Also, Digital Education Hubs and digitally supported Regional Training Centres can increase the number of teachers who are considered qualified according to national standards. Globally, around one teacher in seven does not have this level of qualification, risking sub-par educational outcomes for their students. For example, Mobile Innovation Hub: Platforms for Tomorrow is an accelerator program to support local and digital innovation ecosystems by facilitating investment, helping to build start-ups and delivering training.

A good example of a thematic digital educational hub is the Dutch project Club of Hubs "Digital Calendar Blocks" (`https://cultuursnack.nu/`, Arnhem, the Netherlands). The hub unites all participants in the educational process, as well as museums, libraries, archives, etc. Tools for creating and using educational materials on smart boards and tablets in the form of calendars on a certain topic are offered on the hub's free digital platform. Members of the hubs club can create their own digital calendars, share experiences, and use the resources of other hubs. Most digital calendar topics can be used to teach history, geography, languages, media literacy, biology, and technology. They also contain topics of civic education. CE is implemented in the Netherlands across all subjects. For example, the themes "Helderland memories – 75 years of freedom" and "Battle of Arnhem" are dedicated to the events of the Second World War and the liberation of the Netherlands from fascism. The cities of the Netherlands are told by the calendars "Eindhoven", "Valkenswaard", "View of Arnhem", "Digital block calendar South Holland", and "Breda, 2019 view". These calendars contain interesting facts related to a certain city of the Netherlands and have photos in thematic blocks. Each block can be accompanied by meaningful text, dates of events, questions for discussions, and topics for research. The space of the digital educational hub can be developed and integrated into the digital educational environment of the educational institution (school, teaching office, higher education institution, extracurricular education institution, etc.). The educational digital hub for CE supports the school subject "People and Society", it was created in the educational environment of the leading Flemish publishing house "Die Keure" (`https://www.diekeure.be/educatief/hub/`),

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which takes active participation in the process of education development in Belgium. The functioning of the Digital Education Hub of Flanders is aimed at such important aspects of CE as the formation and development of civic, communicative and ICT competencies, as well as competencies related to financial literacy, cooperation, etc. The publishing house has created an original methodology for teaching subject "Man and Society" in a secondary school in the Dutch-speaking part of Belgium. The teacher can work based on the modular method. Six thematic electronic journals are offered for working with students. Six modules can be used in any sequence. E-zine topics include elements of civic education, including Life, Nutrition and Health, Back to Business: Entrepreneurship and Charity, Game On Gaming and Social Media, Passage: Travel and Nature, "Grinta: sport" and "Fear of Public Speaking: music, cinema and theatre". The publishing house created an online educational platform "POLPO" (`https://www.polpo.be/`) for teachers. Educators can use resources and tools to create their learning designs, apply a differentiated approach to teaching, and evaluate both students and themselves. An educational hub can function both by itself and as part of a network of hubs. The network can be deployed purposefully, and hubs can join the network themselves, attracting new members. The national network of multimedia education in the Netherlands "Filmeducatie" (`https://www.filmeducatie.nl`) supports citizenship education. "Filmeducatie" launched a project to create a National Network of Multimedia Hubs in Education in 2019. The project is gaining popularity and the network of hubs is expanding. Pupils, students of pedagogical institutions of higher education, teachers and lecturers from universities, parents, and civil society organisations can cooperate in hubs. Everyone can collaborate, propose ideas, get involved in projects, use resources, educational materials, video lessons and lectures, attend educational and cultural events, school performances, museums, libraries, etc. Digital educational hubs offer professional development courses for teachers. Teachers can remotely develop civic and digital competencies, learn new methods and forms of work, and use multimedia tools and ICT in professional activities. "From critical viewers and media creators to creative conscious citizens" is the mission of the Film HUB Gelderland hub. For the 75-th anniversary of the commemoration of the end of the Second World War, celebrated in the Netherlands in 2020 at the national level, a package of lessons "75 years of Freedom – War and Freedom in Pictures" has been created for teachers in the digital education hub "Beeldung". Teachers of civic education and teachers of other subjects who implement it in their lessons can use educational materials, show films and discuss with students the topic of war, human rights, democratic values and freedoms. Conceptually, the construction of the hubs of the National Network of Multimedia in Education of the Netherlands "Filmeducatie" is maintained in a single key, which is reflected on the Internet pages: an interactive map of the province is divided into municipalities and contains info-graphics that offer information about current events that take place in the field of film and media education, offers of cinemas, festivals, events in cultural centres, libraries, organisations and institutions of the province. The teacher can select the necessary resources for working with students using filters. This allows you to search by level of education: primary, secondary and senior, as well as by type of event, and type of activity. Information about educational platforms, cultural and educational coordination centres, schools that have joined the hub, etc. are collected in digital educational hubs. Teachers who have joined the work in the hub post their web pages, pages on social networks, and blogs. The hubs' web pages offer news, interesting facts, articles, issue newsletters and much more. You can also join the hub via the pages of social networks Facebook, LinkedIn and Instagram.

The creation and deployment of educational hubs is also inherent in Ukrainian education, which is associated with the impact on the educational environment of such factors as the rapid development and penetration of digital technologies into educational processes, the need to switch to remote forms of education for schoolchildren during the COVID-19 pandemic, and limiting access to school infrastructure in wartime.

In 2020, the Ministry of Digital Transformation of Ukraine initiated the creation of a network of digital educational hubs across the country. These hubs were established in libraries and other public places and were equipped with computers with Internet access. Such an initiative was carried out with the aim of providing an opportunity for everyone to come and learn how to use digital tools and resources and acquire digital skills. Also, for the organisation of training, UNDP and Sweden over the past three years supported the Ministry of Digital Transformation of Ukraine in building a network of hubs, as well as training their coordinators and users.

The number of Ukrainian educational hubs is growing every year. Among them are: "Osvitoria Hub", Kyiv (`https://hub.osvitoria.org`), "Spalah", a network of educational hubs (`https://spalah.com.ua`), "HUB School", Vinnytsia (`https://hubschool.com.ua`), "World School Hub", a network of licensed international schools in Ukraine (`https://worldschool.com.ua/`), international network "Impact Hub" (`https://impacthub.odessa.ua`), "Long Hub", Dovge, Transcarpathia, independent educational corporation "TeachHUB" (`https://teach-hub.com/`), "Kid's hub" network of the public organization "Crimean Diaspora", "Education HUB" (`https://edhub.com.ua/`) and many others are currently operating in the Ukrainian educational space. "Educational Hub of the City of Kyiv" is a powerful tool of the Ukrainian information and digital educational environment (`https://eduhub.in.ua`). This hub has a resource base that works in the format of blended learning, provides training and testing for the development of soft skills, promotes lifelong education and supports sustainable development. Meetings with successful and well-known Ukrainian political and cultural personalities are held on the grounds of the "Club of Prominent People" of the "Educational Hub of the City of Kyiv", intellectual games championships are held, professional orientation events and much more are organized. The implementation of civic education is carried out by the "Learning Hubs" network, which involves 40 schools in Zakarpattia, Donetsk and Luhansk regions. One of the initiatives is the educational project "Active Citizens". The project gathered active young people to create changes on the ground. Creating conditions for interaction and cooperation of teachers, professional mastery groups are held in the hub. As the members of the Network note, partnerships and cooperation contributed to its creation. Uniting hubs into a network allows coordination of joint actions, helps to strengthen organisational potential, helps to join efforts for the implementation of ideas and projects, to learn and exchange experience. An educational hub can function both independently and as part of a network of hubs. A network of hubs can be deployed purposefully, and independent hubs can join the network and attract new members to it.

Educational institutions train teachers, carry out teacher training and are involved in the process of creating hubs. Thus, the All-Ukrainian Educational Hub of Pedagogical Innovations of the New Ukrainian School was created based on the Cherkasy Regional Institute of Postgraduate Education of Educators of the Cherkasy Regional Council in 2020. It became the basic centre for the accumulation and distribution of the author's methods, technologies, models of the educational process and management activities, innovative methods and forms of work, and professional development of teachers.

"Skills Hub" of the Pavlo Tychyna Uman State Pedagogical University is an example of the implementation of CE and its elements. Participants learn "soft skills" at workshops and seminars, learn teamwork skills, and time management (optimal organisation of time to solve current tasks) and develop civic competence. Pupils and students are offered to create and make speeches in the format of "TED Talks" – a project of the US non-profit organisation "TED Conferences" (`https://www.ted.com/`). The project has been spreading "ideas that will change the world" since 2006. A collection of audio and video files of the best speeches, which can be accessed for free, is available on the Internet. Since 2017, civics education has been fully implemented in programs for grades 5-9. This approach requires training of teachers, providing them with high-quality educational materials and free access to them. Today, few educational environments are aimed at forming the civic competence of teachers and students. The website of the "New Age" project of the All-Ukrainian Association of Teachers of History and Social Sciences "3D-Democracy" – "Citizen's Workshop" (https://citizen.in.ua/about.php) and the educational platform "We Live in Democracy" (https://living-democracy.com.ua/) are actively working.

The educational platform "Living in Democracy" (https://living-democracy.com.ua/), launched as part of the Swiss-Ukrainian project "Development of Civic Competences in Ukraine – DOCCU" with the assistance of the Government of the Swiss Confederation, offers resources of the Council of Europe with education for democratic citizenship to conduct lessons and events on the topics of democracy, human rights and civic participation. The web pages of the platform contain educational materials, legal documents, video materials, illustrated cards about children's rights, and several Council of Europe manuals, in Ukrainian translation, including: "Teaching democracy", "Growing in democracy", "Living in democracy", "We take participation in democracy", "Exploring children's rights" and "Teaching democracy". Pupils, parents, teachers and school leaders can find useful information on social welfare issues, learn, develop and improve themselves. The digital educational hub, as already mentioned, is an environment for joint educational activities. The current state of ICT development offers a wide variety of tools to make the hub full of ICT, which will make access to it open and provide an opportunity to more fully realise its functions. The hub can be created for a separate subject, topic, project or educational direction. The resources posted on the website of the 3D-Democracy project "Citizen's Workshop" (https://citizen.in.ua/about.php) are aimed at supporting students and teachers of civic education. The educational platform "Living in Democracy" (http://www.living-democracy.com.ua), launched as part of the Swiss-Ukrainian project "Development of Civic Competences in Ukraine – DOCCU" with the assistance of the Government of the Swiss Confederation, offers resources of the Council of Europe with education for democratic citizenship to conduct lessons and events on the topics of democracy, human rights and civic participation. The web pages of the platform contain educational materials, legal documents, video materials, illustrated cards about children's rights, and several Council of Europe manuals, in Ukrainian translation, including: "Teaching Democracy", "Growing in democracy", "Living in Democracy", "We take participation in democracy", "Exploring children's rights" and "Teaching democracy". Pupils, parents, teachers and school leaders can find useful information on social welfare issues, learn, develop and improve themselves. The digital educational hub, as already mentioned, is an environment for joint educational activities. The current state of ICT development offers a wide variety of tools to make the hub full of ICT, which will make access to it open and provide an opportunity to more fully realise its functions. The hub can be created for a separate subject, topic, project or educational direction. The resources posted on the website of the 3D-Democracy project "Citizen's Workshop" (https://citizen.in.ua/about.php) are aimed at supporting students and teachers of civic education.

After reviewing the existing experience we propose to create digital educational hubs to support civic education based on educational institutions, which can serve as a component in the digital educational environment and contribute to the achievement of the goals of sustainable development. The digital educational hub, as already mentioned, is an environment for joint educational activities. The current state of ICT development offers a wide variety of tools that allow for open access to the hub and more fully implement the hub's functions. The hub can be created for a subject, topic, project or educational topic. Figure 1 presents the author's vision of a digital resource hub to support CE. Therefore, a digital resource hub for civic education may include the following resources: manuals and methodical recommendations on CE; bank of ideas and innovations; online networks with CE (domestic and international); access to participation in CE projects; student initiatives and SE portfolios; portfolio of teachers who teach civic education or implement its elements in their lessons; questionnaires, tests and monitoring tools; platforms for communication and exchange of experiences among colleagues, students, and parents.

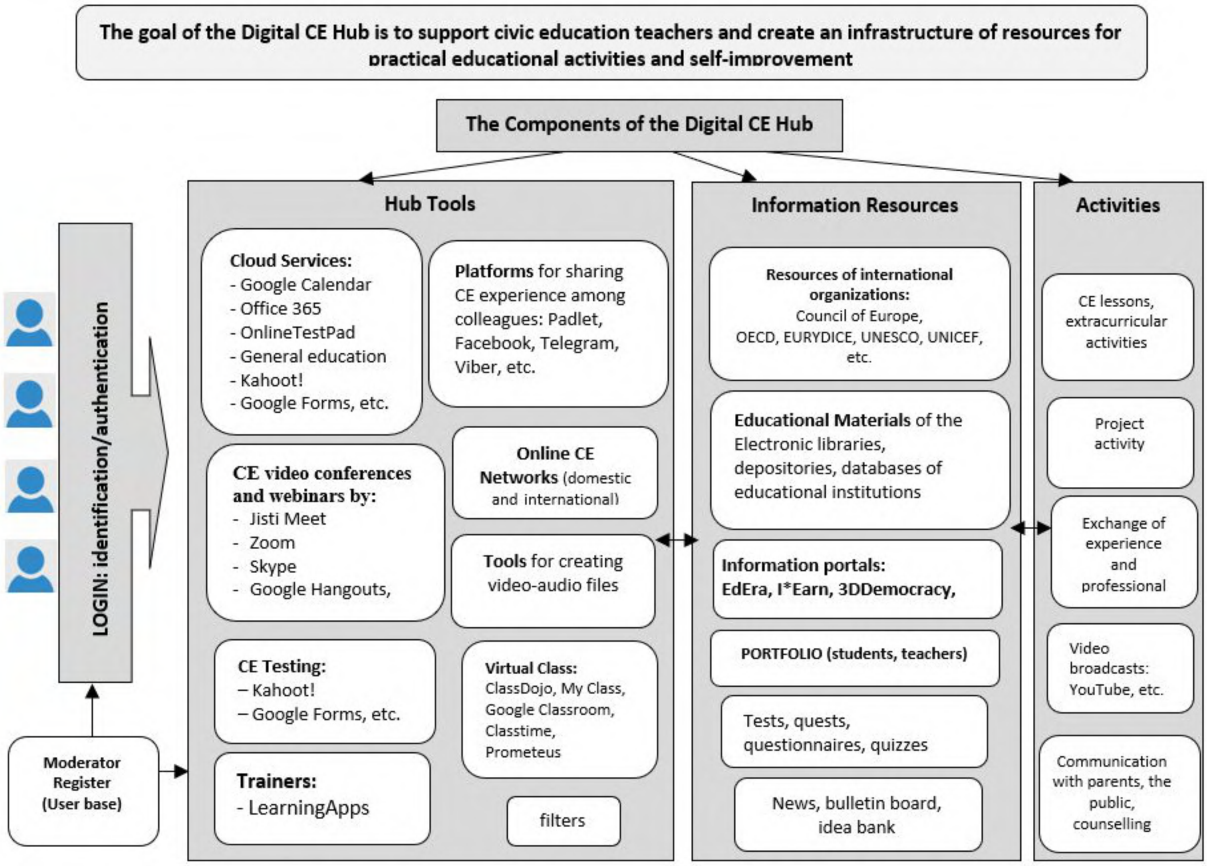

Figure 1. The vision of the digital hub for civic education (CE) support in schools.

Therefore, a digital hub for civic education (CE) may include the following elements: 1) conceptual and strategic documents on CE issues: legislative documents and concepts in the field of general secondary education, educational standards, strategies for implementing CE in the education system in Ukraine, international declarations and conventions in the field of human rights protection, relevant recommendations of the Council of Europe, UNESCO, UNICEF, UN and other international institutions working in the field of human rights protection and civic education; 2) CE manuals and methodological recommendations (domestic and international developments for the implementation of civic education, standards and framework approaches, curricula and thematic modules, references to the legislative framework of Ukraine on the protection of human rights and international documents, declarations and conventions in the field of human rights protection); 3) references to the online CE networks (domestic and international): a list and links to networks offering informational materials, and educational resources for improving the qualifications of teachers in the field of civic education; 4) access to participation in CE projects: descriptions and links to civic education projects implemented in Ukraine and abroad, eg. The Democratic School Project (European Wergeland Center, Oslo, Norway); 3-D Democracy project (Nova Doba Association) etc.; 5) references to the student initiatives and portfolio: description of student research, projects, examples and results of competitive student works, including works submitted to thematic Olympiads, creative works, and festivals; 6) banks of surveys and monitoring tools: questionnaires and data, tasks, quests, test tasks and examples; 7)links to the platforms for sharing experiences among colleagues, students, and parents; links to professional pages on social networks Facebook, Linked In, and Instagram, web pages, portals, platforms and resources for sharing experiences, blogs, YouTube channels, other digital resources of professional communities on CE issues; 8) bank of ideas and innovations for further implementation and development of CE in school: project proposals, methodical developments, scenarios of CE events; 9) electronic libraries and databases: links to libraries, and depositories, including state institutions, research organisations, museums, cultural centres, and public organisations (domestic and international).

Technical support of the digital educational hub for the implementation of CE should include a set of services aimed at ensuring the reliable, safe and secure functioning of equipment and services of the network, computing and engineering infrastructure of the environment.

Creative teachers should be supported in creating and using digital educational hubs to solve civic education problems. This activity can contribute to their professional and personal development. It is also important to consider the possibilities of civil society organisations offering civic education programs and projects for students and teachers.

Association of Innovative and Digital Education in Ukraine provides support and psychosocial assistance services for children and youth with the financial support of UNICEF in Ukraine. The Project Digital Learning Centers (SPILNO DLC) involves 16 digital learning centers in the communities of Mykolaiv, Odesa and Kherson regions, which will provide catch-up education for students, life lessons on the most popular modern skills of the 21st century related to the Civic Education topics, as well as career guidance, various training and remedial programs, psychosocial support and training for 30 thousand students from 7 regions, as well as teacher training and psychosocial support for teachers and school psychologists (`https://www.aide.one/en/projects`). Training courses for teachers, dedicated to subjects related to civic education, such as “Media Literate Resistance: Building Reasoned Dialogues” and “Media Literate Resistance: Communicating on Equal Terms” have been developed for teachers within the framework of the project “Study and Distinguish” with the support of IREX on the SPILNO platform (`https://eduhub.in.ua/category-course/onlayn-kurs-mediagramotniy-sprotiv`).

The importance of research and surveys of teachers and students that highlight the experience of civic education in different countries should also be emphasized. This is important for highlighting the best practices of teaching civic education and developing own methods, models and approaches to support civic education, including through digital educational hubs.

Digital educational hubs to support civic education are a relatively new phenomenon in education and this is related both to the significant quarantine period when teachers were forced to teach online, and to the development of technology and the transition to new technological solutions in education, and most importantly, the need to provide access to resources and training for teachers and students.

The best-known international research is the International Civic and Political Education Survey (ICCS), which is conducted every five years and assesses the knowledge, skills and attitudes of 8th-grade students in civic education (`https://www.iea.nl/research/iccs`); The Program for International Student Assessment (PISA), which is conducted every three years, includes a citizenship education module that assesses the knowledge and skills of 15-year-old students (`https://www.oecd.org/pisa/`); The European Values Study (EVS), conducted every nine years, examines the values and attitudes of citizens in various European countries, including issues related to citizenship education (`https://www.europeanvaluesstudy.eu/`).

Digital civic education hubs are important tools for disseminating knowledge about civil rights, democracy, social justice, and other aspects of civil society. These hubs provide access to learning materials, interactive resources, information sources and communities for acquiring citizenship knowledge and skills.

Having analysed the support of civic education through digital educational hubs and taking into account that civic education and education for democratic citizenship in different countries can be considered as an integrated course, a framework, or a program, certain approaches to the implementation of this direction should be singled out: a) at the political level: support for digital civic education hubs can be implemented through the initiation of programs, including cooperation programs with international organisations, such as UNICEF, UNDP, the Council of Europe, and the international technical assistance programs. Governments can develop national strategies and frameworks that recognise the importance of understanding the role of citizenship education from regional and national perspectives; b) in the classroom: civic education can be taught as an integral part of existing subjects – from geography to social studies, using the resources of digital educational hubs and projects containing civic education topics; implement school projects and create digital school communities for civic education; teachers can incorporate materials that build awareness of civic values. For instance, in Geography and Social Sciences, pupils can learn about countries and their political systems. Teachers can also assign students a group digital project where they will have to devise a campaign to address civic knowledge in their local community; c) at the level of professional development of teachers: use the opportunities for professional development in the use of digital educational resources, in particular from CE, as well as other subjects to acquire digital skills and master new methods, practices and methods of learning; d) at the level of civil society and out of class activities: to engage the capabilities of public organisations, including the created digital hubs to engage teachers and students in communication and learning about civic education and with the civic society, the initiation of educational activities for a broad interested public on issues of civic education.

4. Conclusions

Having conducted an overview of the existing experience of the use of digital educational hubs in the field of civic education conclusions and recommendations can be useful. Civic education is an important part of sustainable education and development allover the world. Turning to the issues of civic education and education for sustainable development, it should be noted that Ukrainian school programs do not provide separate subjects from these topics, and Civic Education as a separate subject is studied for only one year in the 10th grade. Sustainable development as a concept remains insufficiently mastered by the teachers, who are focused on teaching subjects and testing students' acquired knowledge. Cross-cutting skills and abilities (soft skills), which should be the result of education for sustainable development and the formation of competencies for democratic citizenship, are very important in the process of assessment of the students' achievements.

The latest changes in the shift to the distance and blended mode of learning proved the effectiveness and usefulness of effective digital technologies when teaching CE in schools. It refers to the wide and open access to CE information resources, widening the possibilities to communicate without borders, and to obtain knowledge at any time and place etc.

The author's vision of a digital resource hub to support civic education is presented in the main components (digital tools resources and activities) that are aimed at the support of civic education teachers to create and use an infrastructure of resources for practical educational activities and self-improvement. It is worth paying attention to such recommendations regarding its components as a bank of ideas and innovations for further implementation in the educational process; digital platforms for communication and tools for evaluation and questionnaires; hub pages in social networks, blogs and sites of teachers conducting training, seminars, lectures, workshops.

A digital civic education hub can be created based on a general secondary education institution, an out-of-school education institution, a post-graduate education institution, a civil society organisation, a scientific institution, or be a part of the regional educational authorities and professional teachers' associations. It is important to provide the tools of the digital educational hub with free access and adjustment of the organisation of distance learning and the opportunity to join the educational process for all those interested, regardless of their location and time. The functioning of the digital educational hub should be focused on the development of civic competence and, at the same time, digital competence through the integration of elements of online learning and the use of digital tools for the dissemination of civic education. The digital educational hub for civic education is an element of the information and digital educational environment, modernises and strengthens it, ensuring the development of civic and digital competence of participants in the educational process; digital educational hubs can be used to create thematic, branch, subject, etc. educational environments; creation of a network of digital educational hubs on issues of civic education will contribute to ensuring the quality of education in general. As stated in Goal 4 "Quality Education" of the Concept of Sustainable Development [30], education is "one of the most powerful and proven means of sustainable development" and plays an important role in the formation of a citizen and the development of a civil society built on the principles of democracy.

It was also explored that digital education hubs offer different support for the implementation of citizenship education. This includes the placement of educational materials, project activities, professional communities for teachers and thematic communities for students, resources and links for familiarization, exchange of experience.

Since civic education is an integrated direction in the school curriculum, it is worth paying attention to such important aspects as continuous professional development of teachers regarding the use of digital tools for social science subjects, motivation and involvement of teachers in professional communities, joint learning and exchange of experiences, psychological support of teachers. It is also important to work outside the classroom with students, involve civil society in the implementation of student projects, create opportunities for dialogue and exchange of opinions. Equally important is the technical support of digital educational programs and their popularization among parents and school leaders.

The conducted research does not exhaust the interest in finding better opportunities for Ukrainian teachers and students regarding the development and use of digital educational hubs for civic education. Ukrainian students and teachers need to get acquainted with the experience of foreign countries, to implement the best practices of using digital tools for civic education.

Therefore, further research is needed to study the forms and methods of using digital educational hubs for teaching school subjects in different countries, in particular civic education, monitoring the activity of students in such hubs, and studying the interests of students for further education and expanding the range of opportunities for students and providing them with open access to educational opportunities regardless of location and current situation in the country.

The perspectives of further research also can be realised in the field of ensuring scientific and methodological support of digital sustainable education in schools; teachers' professional development in the field of the use of ICT for CE teaching; monitoring of the influence of digital technologies and in particular the use of educational hubs on the results of students' achievements.

A digital educational hub for civic education, where the teacher has free access to electronic resources, online tools for the development of educational materials, evaluation, testing, surveys, involvement in online platforms for education, professional development, communication and exchange of experience, etc. at any time and in any place, can contribute to the solution of the problems that have deepened the educational gaps caused by the military aggression of the Russian Federation against Ukraine.

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Artificial intelligence, the labor market, and education for sustainable development: the points of intersection

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Artificial intelligence, the labor market, and education for sustainable development: the points of intersection

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Abstract. This scientific paper is devoted to clarifying the relationship between artificial intelligence (AI), the modern labor market, and Education for sustainable development. Within this study, the authors concentrate their efforts on the following directions: (1) exploring the existing educational approaches and techniques, the knowledge of which helps minimize the possible negative consequences associated with the implementation of AI into the labor market; (2) analyzing Ukrainian and Slovak students' points of views, that were obtained by surveying, on AI technologies and their potential effects on the labor market; (3) providing substantiation regarding the need of using the pedagogical strategies, particularly, (a-b) the implementation of AI-related technologies in the professional cycle disciplines, (c) assigning tasks that require AI technologies to exploit, (d) exploiting AI technologies as the source of improving the information infrastructure in HEIs. While formulating these pedagogical strategies, the authors comprised possible consequences (a negative effect of AI on the labor market, risks of applying AI in all spheres of human activity, a negative attitude of students toward AI) of AI application and the planned results. The authors considered the five dimensions of sustainability (technical, social, environmental, user, and economic) and presented them in the format of the Sustainability Awareness Diagram (SAD). The visualization of the effects that may result from the use of pedagogical strategies for Education for Sustainable Features is suggested. Each planned result is put in the SAD, assuming their influence (immediate, enabling, structural) on Sustainable Features. In overall, the proposed strategies aim to reduce the potential negative impacts of AI on the functioning of the labor market and instill a positive attitude toward AI technologies in university youth. The findings comprise the multifaceted and dynamic relationships between AI, the modern labor market, and Education for sustainable development. Results also reveal that AI technologies significantly impact the labor market by influencing job roles and skill requirements. Correspondingly, Education for sustainable development is vital in preparing young people to be aware of the evolving demands of the labor market impacted by AI, promoting skills that align with both technological improvements and sustainable practices.

1. Introduction

Today, science engages in further scientific explorations of the questions related to AI and its effect on life. We look at some of these questions through the lens of this research. How has AI affected the labor market? And what are the forecasts for the impact of AI? What research reveals matters? Is a sustainable future at risk? These concerns are in our field of view. This study delves into the reality of AI being a part of life. It is worth noting that the day-to-day goal of the Sustainable Futures concept and the Sustainable Development Goals is to ensure sustainable development that satisfies the needs of today's life without compromising the knowledge of future generations to meet their needs. Nowadays, the world faces many challenges that hinder the development of Sustainable Futures [1]. Let us mention that the published report by the World Economic Forum, "Future Focus 2025: Pathways for Progress from the Network of Global Future Councils 2020–2022" [2], concerns detail the global challenges and offers considerations on how to confront them in terms of the Sustainable Futures concept. Among others, we focus on the following essential information and pay attention while reading the document: challenges within the economy (righting the economic course, the impact of extreme wealth inequality, a self-perpetuating system), challenges and the environment (climate change, air pollution, water scarcity, natural resources depletion), challenges and society (government action and corporate governance, access to education, health care, and opportunities, protecting vulnerable populations), challenges and technology (concerns about AI capabilities).

Moreover, according to the World Economic Forum, one of the new areas of concern facing our world is the development of artificial intelligence (AI), especially regarding its impact on the labor market [3]. The development of AI raises concerns about replacing human labor and automating work tasks, which will lead to the loss of jobs. Companies' expectations from employees are also changing: more and more vacancies require AI competencies. AI and Machine Learning Specialists top the list of fast-growing jobs [4]. Approximately 75% of companies surveyed said they plan to adopt AI technologies over the next five years, and this situation is projected to lead to losses in administrative positions as well as traditional security, factory, and sales positions by 2027. According to the report "Generative AI and the Future of Work in America", in the United States, by 2030, it will be possible to automate everyday activities that account for up to 30% of working hours. This trend will be accelerated by generative AI, office support, customer service, and food service employment, which could continue to decline [5]. Employment Outlook, a review of new evidence on the influence of AI on the labor market, emphasizes the significant uncertainty surrounding the current and especially future impact of AI on the labor market [6].

Solutions to these issues are proposed in politics, law, and business. In particular, Del Pero and Verhagen [7] point out that most countries primarily rely on soft law for AI-specific matters. Still, several countries are developing new AI-specific legislative proposals applicable to AI in the workplace. The report [3] raises questions that need to be addressed at the level of companies and business leaders, policymakers, and individuals as workers, consumers, and citizens. In particular, the extent to which people should be concerned about the emergence of generative AI and how workers and consumers can balance the convenience of generative AI with its impact on their workplaces. At the same time, the attitudes of students as future workers in a rapidly changing society towards AI technologies and the role of higher education institutions in addressing the impact of AI technologies on the labor market in terms of sustainable development education still need to be studied.

2. Literature review

Do the points of intersection between AI, the labor market, and education for sustainable development exist? This question became the topic of discussion for researchers, citizens, and university students. In line with the theme of this research, we present the literature analysis on the risks of introducing AI into the spheres of human activity. The study also involves the exploration of scientists' opinions on this matter. Moreover, we delve into the educational sphere and look at it through the prism of sustainable development. In the research process, we were motivated by the following question: Is there any experience through education that can solve the problem of AI's influence on the labor market?

To answer these questions, we focused on the scientific works on the risks of using AI in human activity related to the labor market. In this regard, we note that the wide use of AI can lead to large-scale unemployment in the future [8]. Furthermore, AI has the potential to deepen the gap between developed and developing countries, as well as raise the demand for specialists with extraordinary talents, lead to job loss or drive down wages of less-qualified staff, dwindling tax revenues, and this shift has negative consequences on the labor market in general [9]. Salaries or wages could decline for workers involved in smaller amounts of less work due to automation [7]. Moreover, using AI leads to the emergence of new forms of video surveillance camera systems in workplaces. Also, increased workplace automation leads to adapting to the changes, leading to further labor market opportunities. Automation of workplaces can also lead to the loss of jobs by individuals [10]. Overall, the risks of introducing AI into areas of human activity are closely linked to the labor market, affecting employment opportunities and dividing the labor between humans and AI technologies depending upon where each excels.

To minimize these risks, scientists are constantly seeking solutions. Well-thought-out strategies, approaches, and tactics related to AI can minimize negative consequences [9].

Researchers Hassel and Ozkiziltan emphasize that the direct risks inflicted by AI workplace tools can be addressed by proactive regulation. They also point out that the recent EU Artificial Intelligence Act and the Proposal for a Directive on improving working conditions in platform work are two initiatives that are important in addressing the impact of AI technology on the labor market [10]. Also, the General Data Protection Regulation (GDPR) deters unauthorized proliferation of surveillance equipment at work. The GDPR requires companies to obtain employees' consent for using workplace surveillance tools and the data obtained from them. Under this body of rules, companies must obtain the Works Council's approval to launch and use workplace surveillance tools [11]. Addressing and mitigating the discrimination-related risks and challenges arising from using algorithms in labor markets requires dialogue and collaboration among policy-makers, employers and worker representatives, and computer and data scientists. This will help to build an "ecosystem of trust", providing "citizens the confidence to take up AI applications and give companies and public organizations the legal certainty to innovate using AI" [12].

The European Parliament, in its report on a comprehensive European industrial policy on artificial intelligence and robotics [13], partially addressed the indirect risks associated with AI-driven automation. In the document, besides the importance of revising and refashioning labor market policies, social security schemes, and taxation, attention is drawn to the extent of revising and refashioning training and education programs.

European Parliament urges Member States to focus on retraining workers in the industries most affected by the automation of tasks; stresses that new education programs should focus on developing the skills of workers so that they can seize job opportunities within the new jobs created by AI; encourages the development of digital literacy programs in schools, the development of apprenticeships and vocational training priorities to help workers adapt to technological changes.

Therefore, we consider it reasonable, based on studying the attitude of students regarding the impact of AI technologies on the labor market and their future professional activities, to propose pedagogical strategies to reduce the adverse effects of AI on the labor market and the negative attitude of future specialists to AI technologies.

3. Materials and methods

3.1. Methods, data collection tools and procedures

The study is a descriptive (description of the experience of using AI in education for sustainable development), qualitative (literature analysis), and quantitative (questionnaire) study. Within the research, the authors explore the experience of scientists who concentrated on and then summarized their scientific findings concerning the impact of AI on the labor market through education. The authors considered the above-mentioned scientific findings, considering the experience of scientists in solving the issues related to the influence of AI on the labor market through education, modeling an educational approach, and the method of diagrams.

The research also became possible thanks to the application of the Method for Sustainability Design [14]. The authors analyzed the data from the survey conducted at non-linguistic higher schools. The authors surveyed students in Ukraine (Bogdan Khmelnitsky Melitopol State Pedagogical University) and Slovakia (University of Economics in Bratislava, University College Prague) during the fall semester of 2023 and January 2024. We compiled survey data from 24 November 2023 to 15 January 2024. Data collection involved an online survey in Google Forms comprised of 4 questions (Appendix A). When compiling the questionnaire, we used the recent scientific research findings of Dakakni and Safa [15]. Participants, 138 young people, are bachelor's students of non-linguistic higher education institutions – first year students (76.8%), second year students (8%), third year students (4.3%), and a four year student; first year students at the master's program, and a second year student at the master's program (9.4%).

3.2. The aim, objectives, and the research questions of the study

Our scientific research aims to delineate the points of intersection between AI, the modern labor market, and education for sustainable development.

We stated the following research questions (RQ):

RQ 1. Are there educational practices to reduce the risks of introducing AI into human activities for sustainable development?

RQ 2. What are students' attitudes to AI technologies and their impact on the labor market?

RQ 3. What pedagogical strategies can be offered to education for sustainable development to reduce the possible negative consequence that AI can bring to the labor market and the negative attitude of today's students, who are future professionals, toward AI technologies?

To answer these questions, we set the following objectives:

- to analyze the risks of implementation of AI into the spheres of human activity and the proposals of scientists to reduce them in the aspect of education for sustainable development;
- based on the surveying results with views of students from different universities (Bogdan Khmelnytskyi Melitopol State Pedagogical University, University of Economics in Bratislava, University College Prague) and countries (Ukraine, Slovakia), to study the attitude toward AI technologies and their impact on the labor market;
- to propose pedagogical strategies to reduce the possible negative consequences of implementing AI technology in the labor market and the negative attitude of students, who are future labor market specialists, toward AI technologies for sustainable development.

4. Results

4.1. Descriptive findings from the online survey

In line with the second research question, "What is the students' attitude towards AI technologies and their impact on the labor market?", students' answers to the proposed questions were considered (Appendix A and Appendix B).

The analysis of students' answers to the Q1 of the questionnaire – "When applying for a job among hundreds of applicants, I would prefer that humans conduct the screening and selection process to avoid unfairness and error" – shows that 53.6% of respondents are concerned and aware of equity disparities among people and the loss of jobs instigated by AI; 20.3% of respondents are not worried about equity disparities; among people and the loss of employment initiated by AI; 26.1% – are concerned about AI ability to feel, which may render it capable of doing things on its own-likely destructive, aggressive behaviors.

In response to question Q2 of whether humanity is likely to worry about AI taking over jobs, evidence and students' perceptions reveal their concerns. 65.2% of respondents answered that they are concerned about the possibility of displacing jobs because AI will do the work. Note that the range of implications in the economy results in an adaptation of the workforce to the existing situation; AI in the labor market makes young people consider ethical dimensions, accepting the new reality of the nature of employment in the age of AI. However, 22.5% – do not worry that AI will take over human jobs, and 12.3% think AI has garnered a sense of malaise and distrust.

The opinions on the third question – Q3. What do you think about AI and equity issues in terms of machines replacing jobs? – are divided. Young people worry that AI will substitute human beings. Students (40.6% of respondents) adhere to this point of view. Though many students are not concerned about AI and that it can replace people, such a view is shared by 28.3%.

The intersection of AI and privacy notions has become a severe and life-threatening point in contemporary scientific discussion. The deployment of AI technologies raises concerns about data security, surveillance, and the potential loss of personal privacy. Noticing a slight and delicate balance between the transformative power of AI and protecting individuals' privacy poses complex and tricky challenges for officials, technicians, scientists, and society at large. On the Q4. Are you concerned about AI privacy issues? Opinions are distributed as follows: 30.4% think that there are privacy policies on every social media platform; 31.2% have never really thought about privacy concerns; 27.5% have heard about privacy issues all the time but for them getting the job done is more important; only 10.9% have no worries about AI and privacy.

As we can see from the conducted questionnaire, students have shown concerns about AI and the modern labor market, so we need to reduce their anxieties and fears. How? We propose applying the pedagogical strategies to students' university training to answer this question.

4.2. The pedagogical strategies targeted to teaching students at universities to tolerantly perceive the possible adverse effects of AI on the labor market and efficiently alleviate the risk of the hypothetical negative consequences of AI technologies

To equip students with relevant knowledge to tolerantly perceive the possible adverse effects of AI on the labor market and to mitigate the potential negative consequences of using AI technologies (figure 1/the possible consequences), we propose the pedagogical strategies, to be more precise, the instructional strategies (note: according to Dick et al. [16], instructional strategy is used to cover the various aspects of organizing the content, stating learning activities, and determining how to deliver the content and activities) for education for sustainable development.

The schematic representation of the pedagogical strategies targeted at teaching young people at universities to perceive the possible adverse effects of AI on the labor market tolerantly and efficiently alleviate the risk of the hypothetical negative consequences of AI technologies is presented (figure 1).

It is based on the belief that future specialists should be prepared to immerse themselves in the reality of AI technologies. The pedagogical strategies involve using AI-generated content in lessons and AI technologies to improve higher education institutions' information infrastructure.

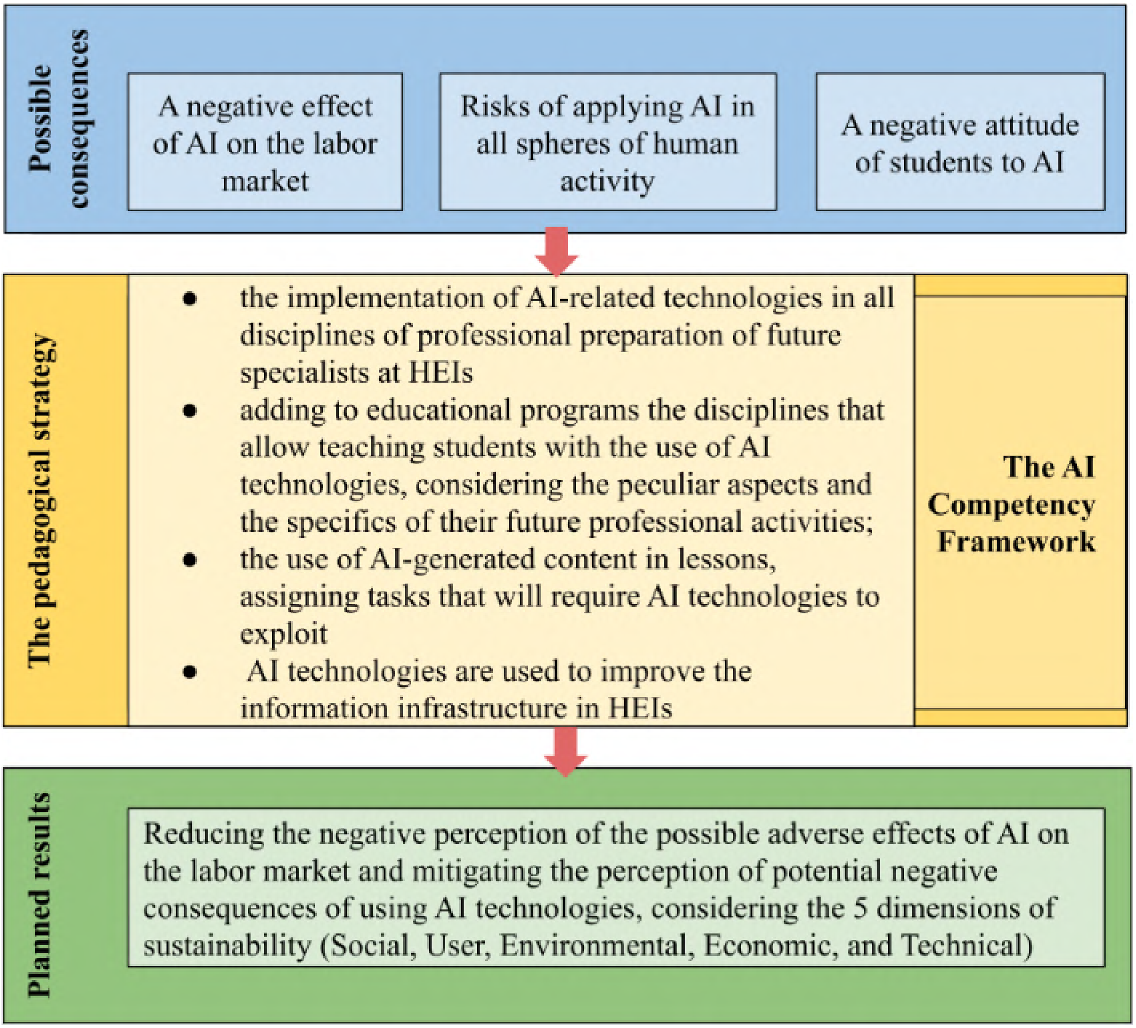

Figure 1. The schematic representation of the pedagogical strategies applicable to the training process to help students tolerantly perceive the possible adverse effects of AI on the labor market and mitigate the perception of the potential negative consequences of using AI technologies.

The pedagogical strategies aim to help cope with the negative consequences of using AI technologies (figure 1/the pedagogical strategy).

Its design involves:

- the implementation of AI-related technologies in all disciplines of professional preparation of future specialists at higher education institutions (HEIs);
- adding to educational programs the disciplines that allow teaching students with the use of AI technologies, considering the peculiar aspects and the specifics of their future professional activities;
- the use of AI-generated content in lessons, assigning tasks that will require AI technologies to exploit;
- AI technologies are used to improve the information infrastructure in HEIs (e.g., distance learning systems, decision-making systems, forecasting systems).

Depending on the university's capabilities, pedagogues can choose the ways of immersing students in AI technologies. However, they can only achieve a comprehensive and sustainable result using these methods simultaneously.

We propose the pedagogical strategies rely on the recommendations of the Artificial Intelligence Competency Framework for higher education institutions [17], even though the AI competency framework is situated in the Montreal AI context; instead, it determines the standard set of competencies required by AI practitioners. This AI competency framework aims to outline the core competencies (knowledge, skills, and abilities) needed by AI practitioners in the technical, business, and human domains. With ethics being integral to the AI field and the work of AI practitioners, ethical competencies have been integrated into the technical, business, and human domains. This competency framework is a tool for various educational roles, including educators, program developers, and prior learning coordinators involved in the program development process from inception to implementation. This framework has more than 70 competencies, which are understood to be the primary knowledge, skills, and abilities required by AI practitioners. In introducing the proposed approach for students of different specialties, selecting those most suitable for a particular specialty from this list of competencies is advisable. For example, it is appropriate for IT professionals to direct their professional training to mastering competencies, which are listed in the “Technical Domain” of the AI Competency Framework.

The authors formulated the planned results that can be achieved when higher education institutions and pedagogues meet the conditions of applying the pedagogical strategies, which reduces the perception that AI harms the labor market and mitigates the negative attitude of young people toward AI technologies. The authors considered the aspects of sustainable development while formulating the planned results (figure 1/planned results). These aspects are considered within the current study, well-thought-out, and matched with the Sustainability Awareness Diagram (SAD) [18]. As a result, the authors complete the diagram entitled “Visualization of the effects that may result from the use of the pedagogical strategies for Education for Sustainable Futures” (figure 2).

We propose the pedagogical strategy, to be more precise, the instructional strategy (note: according to Dick et al. [16], instructional strategy is used to cover the various aspects of organizing the content, stating learning activities, and determining how to deliver the content and activities).

The planned results of applying the pedagogical strategy (figure 1) at the higher education institutions are detailed and presented in table 1.

As mentioned above, each of the five dimensions of sustainability is divided into three levels of impact [18]: immediate – caused by the direct function of the system or its development; enabling – arising from the application of a system over time; structural – referring to persistent changes that can be observed at the macro level. The authors present the visualized version of the effects that may result from using the pedagogical strategies for Education for Sustainable Futures. The authors used the format of the Sustainability Awareness Diagram (SAD) (figure 2).

The authors put each planned result in the SAD, considering their influence (immediate, enabling, structural) on Sustainable Futures.

5. Conclusions

To sum up, it is essential to mention that according to this study, there needs to be more educational practices to reduce the risks of introducing AI into human activity for sustainable development. Such tasks are mostly solved at the legal or state level and by organizations dealing with humankind’s environmental and economic problems. Because of this, a survey conducted among students of non-linguistics universities in two countries testifies to students’ awareness of the disproportion between people and their concern about the loss of jobs because of AI. Many students worry that AI will replace someone (40.6%). Therefore, we

Table 1. Planned results of the implementation of the pedagogical strategy, considering the five dimensions of sustainability.

The dimensions of sustainability	The sustainability of the results
Social	**Education and Social Exchange (EaSE)** The improvement of skills to use AI technology in future professional activities. Contributing to the understanding of AI technology and the ethical aspects of its use in professional activities
User	**Personal experience of using AI in professional activities and everyday life (PEuAI)** Improving the level of professional competence in the AI sphere and the ability to use the knowledge of AI effectively in day-to-day life **Empowering users (EU)** Increasing access to information with the use of AI technologies for lifelong learning **Psychological stability (PS)** Increasing the level of psychological resilience and reducing social tension due to increased confidence in a sustainable future thanks to awareness about AI technologies and their use in professional work
Environmental	**Sustainable Enterprise Management (SEM)** Promoting sustainable development of specialist professional competence to allow sustainable management in enterprises and maintain workers' high professional qualifications **Sustainable Business Practices (SBP)** Promoting sustainable business practices in the enterprise, based on constant innovations and changes that significantly differ from traditional business methods **Sustainable Resource Management (SRM)** Promoting sustainable management of a resource such as a human resource. Thanks to AI technology, employees will be more satisfied, calm, and stress-free because AI will do part of the work, and therefore, they can do more creative tasks, which brings them more pleasure
Economic	**Cost-effectiveness for enterprises (CEE)** Promoting the effective practical work of employees. Saving money that is no longer spent on their training, as they will know how to get knowledge and learn using AI. Therefore, it will increase the profitability of the enterprise **Economic Impact (EI)** The impact on the country's economy through the enterprise's profitability growth
Technical	**Technical safety issue (TSI)** Compliance with the General Data Protection Regulation (EU GDPR) and data protection and confidentiality principles will be a priority during future specialists' training and professional activities

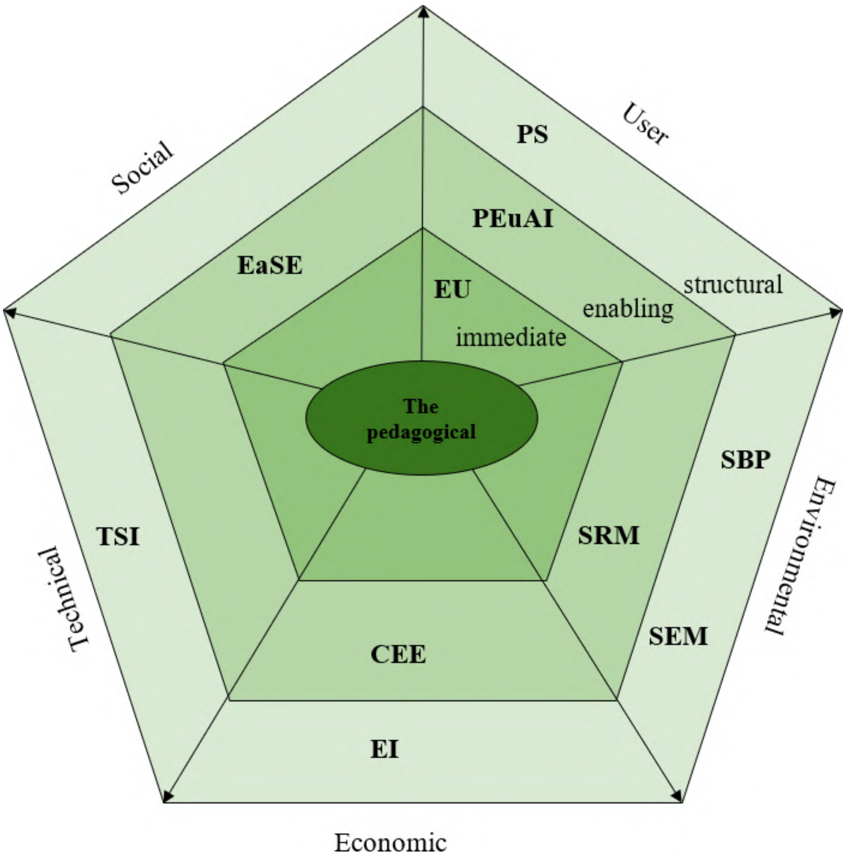

Figure 2. Visualization of the effects that may result from the use of the pedagogical strategies for Education for Sustainable Futures.

have developed the pedagogical strategies to teach university students to perceive the possible adverse effects of AI on the labor market tolerantly and efficiently alleviate the risk of the hypothetical negative consequences of AI technologies. The pedagogical strategies merely start from possible consequences (a negative impact of IT on the labor market, risks of applying IT in all spheres of human activity, a negative attitude of students to AI), offering the solution (the pedagogical strategies) at the level of higher education institutions, taking into consideration the AI Competency Framework, focuses on results aimed at Reducing the negative impact of AI on the labor market and the negative attitude of future specialists to AI technologies for five dimensions of sustainability (Social, User, Environmental, Economic, Technical).

The scientific article explores the intricate interplay between AI technologies, the labor market, and education for sustainable development. The authors investigate the common ground among these factors; the research delves into the multifaceted impacts of AI implementation on employment dynamics, emphasizing the need for the pedagogical strategies that align with principles of sustainable development. The article critically analyzes the challenges and opportunities within the nexus of AI, the labor market changes, and sustainable education, offering ideas for pedagogues that help to find the path to teach students to navigate the everchanging technology landscape, support the employees, whose work can never be replaced by automation, to foster both technological advancement and well-being of society.

Acknowledgments
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Appendix A. Questionnaire

The survey was compiled using the research finding of Dakakni and Safa [15].

AI and equity

Q1. When applying for a job among hundreds of applicants, I would prefer that the screening and selection process be conducted by humans to avoid unfairness and error?
Response options
- I am concerned and aware of equity disparities among people and the loss of jobs instigated by AI (I am aware of a dark side of AI as concerns about bias and inequity)
- I am not concerned with equity disparities among people and the loss of jobs instigated by AI
- I am concerned about AI's ability to feel, which may render it capable of doing things on its own-likely destructive, aggressive behaviors

Q2. Do you think humanity is likely to worry about AI taking over jobs?
Response options
- Yes, I do. AI has garnered a sense of malaise and distrust
- Yes, I do. I am concerned about the possibility of AI technology displacing jobs and labor
- No, I do not

Q3. What do you think about AI and equity issues in terms of machines replacing jobs?
Response options
- I do not have any concerns about AI replacing people or equity issues. I feel technology creates jobs in another form for people
- I worry that AI will substitute human being, but I cannot deny the fact that it is very helpful
- I am against AI taking over jobs. Honestly, I am afraid of this happening in the future
- I do not think AI separates people, but it could become a threat because people have detected feelings in the answers of AI, so it is closer to a human that you interact with. It can start doing things on its own. Now, that is scary

AI and Privacy

Q4. Are you concerned about AI privacy issues?
Response options
- No, I have no worries about AI and privacy
- I have never really thought about privacy concerns. This is not something I stop to think about
- Yes, I hear about privacy issues all the time, but to me getting the job done is more important

- I think there are privacy policies on every social media platform; just do not go into the dark web because there are no agencies that can protect you from hackers and people using the dark web for illegal causes. I think, the rest is safe

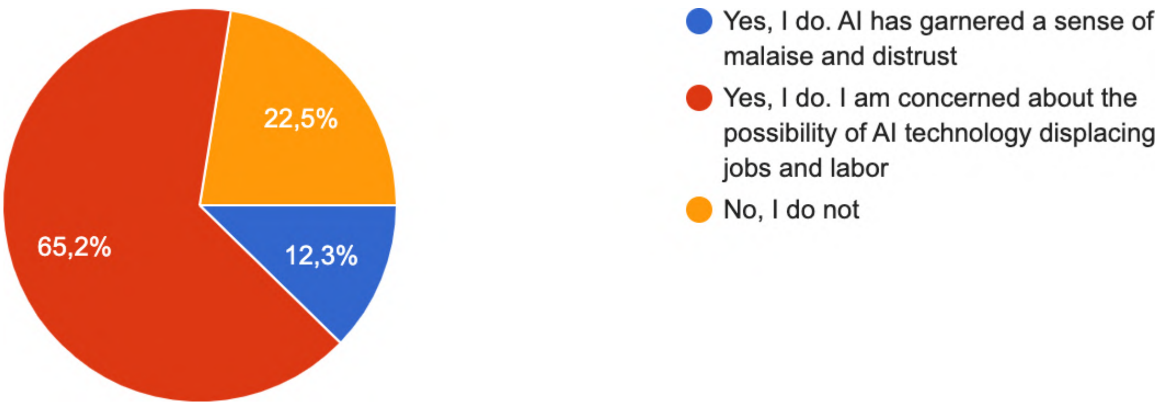
Appendix B. The questionnaire questions and the students' choice

The survey was compiled using the research finding of Dakakni and Safa [15].

AI and equity

Q1. When applying for a job among hundreds of applicants, I would prefer that the screening and selection process be conducted by humans to avoid unfairness and error?

Q2. Do you think humanity is likely to worry about AI taking over jobs?



Q3. What do you think about AI and equity issues in terms of machines replacing jobs?

AI and Privacy

Q4. Are you concerned about AI privacy issues?

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Geoinformation assessment of solar plant potential in the Ivano-Frankivsk region to achieve effective decarbonisation and energy stability

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Geoinformation assessment of solar plant potential in the Ivano-Frankivsk region to achieve effective decarbonisation and energy stability

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Abstract. Despite the ongoing hostilities in Ukraine, the country has begun its recovery process. The renovation should be in line with the principles of energy efficiency and decarbonisation, with an emphasis on the use of renewable energy sources. The study aims to identify the most suitable locations for establishing solar power stations in the Ivano-Frankivsk region using GIS software. It also provides a cartographic model showing the suitability of different areas for local communities, providing valuable information for potential investors. The calculation process was carried out using QGIS, incorporating environmental, technical and economic factors, and resulted in the development of a conclusive suitability map. The primary assessment of photovoltaic potential was conducted for communities within the Ivano-Frankivsk region. The areas with the most promising potential, estimated to be over 50 MW, were ranked according to their suitability for solar plants.

1. Introduction

Decarbonisation involves decreasing carbon dioxide and methane, which are responsible for the greenhouse effect, output per unit of electricity generated [1]. As the global community intensifies its commitment to combat climate change and transition towards sustainable energy sources, the imperative for effective decarbonization and energy stability becomes increasingly pronounced. In this context, renewable energy, particularly solar power, emerges as a pivotal player in fostering a cleaner and more resilient energy landscape [2]. Ukraine aims to achieve decarbonization as part of its commitment to combat climate change and meet international obligations by reducing greenhouse gas emissions [3, 4]. Meanwhile, Russia's war against Ukraine continues, causing significant damage to infrastructure, housing, and natural habitats in Ukraine. Rebuilding the affected areas will inevitably lead to increased emissions from construction activities and the operation of new businesses. While solar energy is a crucial component of the decarbonization effort, a comprehensive approach to addressing climate change involves a combination of renewable energy sources, energy efficiency measures, and changes in consumption patterns [5–8].

Additionally, the integration of energy storage technologies and smart grid systems enhances the reliability and effectiveness of solar power in the overall energy landscape [9, 10]. It is important to realise that the Russian aggression has caused not only significant destruction and damage to energy infrastructure, but also environmental damage that can be described as ecocide. These environmental impacts include changes in the quality of the air over the territory of Ukraine. In the years following the military invasion, there was a significant increase in aerosol pollution [11,12]. Although major pollutants in the air have decreased overall, methane pollution, that significantly contributes to the greenhouse effect, is increasing in Ukraine [13], as confirmed by the results of satellite monitoring by the Sentinel-5 Precursor mission (figure 1).

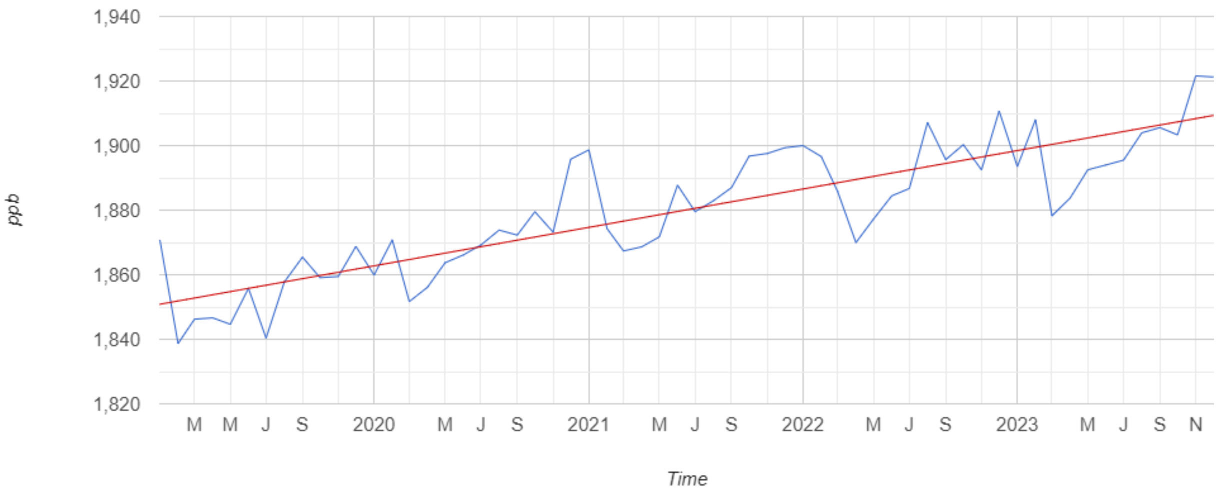

Figure 1. Monthly average density of methane (CH_4) over Ukraine from 2019 to 2023.

Furthermore, the eastern and southern regions of Ukraine, which have the highest solar potential, suffered the greatest losses. This includes damage to solar plants. In contrast, the western regions have lower solar potential due to geographical factors. Therefore, it is crucial to plan and allocate suitable sites for solar plants [14–17].

Geographic information systems (GIS) are the most effective tools for geospatial planning [18]. Most GIS-based studies on site suitability utilize multi-criteria analysis. This method is well-suited for complex issues involving multiple spatial criteria that often have differing units [15,19]. Common techniques within multicriteria analysis include the Analytical Hierarchy Process (AHP), Boolean logic, Weighted Linear Combination (WLC), fuzzy logic, etc. [20]. The Analytical Hierarchical Process (AHP) and Boolean Logic, which have been repeatedly tested to assess the solar potential of different areas around the world [19,21–24], were used in the research to assess the suitability of installing solar plants within the boundaries of local communities.

This article embarks on a comprehensive geoinformation assessment of solar plant potential in the Ivano-Frankivsk region, delving into the intricacies of harnessing solar energy to drive local decarbonization initiatives and fortify energy stability.

The Ivano-Frankivsk region faces an energy deficit, with rising electricity consumption. To enhance Ukraine's energy independence and address depleting fossil fuel reserves, especially given the region's focus on tourism, it's recommended to expand renewable energy use while improving efficiency. Currently, solar energy contributes 1.3% to the region's electricity production, covering about 10% of the population's energy needs [14].

The aim of this research is to analyze spatial suitability to solar plants building and create a cartographic model that visualizes the general suitability of the territorial communities.

In the subsequent sections, we will delve into the key aspects of the geoinformation assessment, presenting results and recommendations to catalyze the realization of a sustainable, decarbonized, and energy-stable future for the Ivano-Frankivsk region.

2. Data and methodology

When planning the installation of a solar power plant, it is essential to consider a range of environmental, technical, and economic factors that impact the solar potential of a territory. Each of these factors plays a crucial role in determining the feasibility, efficiency, and sustainability of the solar project.

In our study, we consider the spatial factors that determine the feasibility or impracticability of siting solar power plants, which have been identified as determinants in a number of publications [25–27]. Environmental factors include climatic (radiation and temperature), geomorphological (altitude, slope, aspect) and land cover. Socio-economic factors include the building, transport network and administrative boundaries of local communities, as well as regulatory restrictions on the siting of alternative energy facilities. An important technological factor is the availability of the electrical network and the possibility of connecting new objects to it. Geoinformation assessment of solar plant potential in the Ivano-Frankivsk region is a multifaceted process that involves considering various factors and environmental constraints regarding site selection and energy yield optimization (figure 2).

Figure 2. Methodology of the research.

Datasets, which were downloaded to assess the optimal placements for solar plants within the region, include region and community administrative boundaries, roads, hydrographic network, forests and parks provided by Research Institute of Geodesy and Cartography (Ukraine) (`https://gki.com.ua/`), electricity distribution and buildings data provided by Open Street Map (`https://www.openstreetmap.org/map`), land using data provided by Copernicus Global Land Service (`https://lcviewer.vito.be`); digital elevation model from EarthExplorer (`https://www.earthexplorer.usgs.gov`), solar radiation data provided by SolarGIS (`https://solargis.com/`) and average temperature data from WorldClim (`https://www.worldclim.org`).

The geoinformation approach combines geographical data with advanced technologies. It was applied with QGIS 3.32 using following steps and tools:

- data collection and geodatabase creation;
- data processing (transformation, clipping and rescaling layers);
- buffering, Boolean selection, overlay, Analytical Hierarchy Process;
- creating evaluation and constraint maps;
- combining maps – creation suitability map;
- zonal statistic – assessing administrative areas photovoltaic potential;
- thematic cartography and visualisation.

These tools provide a comprehensive understanding of the region's solar energy potential and aid in making informed decisions [28–31].

To prepare the downloaded data for AHP analysis and site selection algorithms, the following steps were completed: converting data to the single coordinate system, clipping vector and raster layers for analysis, creating buffer zones, and converting vector data to raster format. This process resulted in constraint maps indicating suitability of areas for solar power plants, with 0 representing unsuitable areas and 1 representing suitable areas, used for Boolean analysis. The next phase involved generating a slope map from digital elevation model (DEM) and further clipping raster data. It was important to standardize the varied units of raster layers (e.g., solar irradiation, slope, distance from power lines, temperature) to a uniform scale using linear scaling, which normalizes data across a common numerical range. This standardization facilitates accurate weighting and comparison in AHP analysis. The Boolean logic algorithm transforms the data from each raster map into binary form, using 0 and 1 (representing false and true, respectively). Consequently, areas deemed completely unsuitable are assigned a value of 0, while areas considered suitable are given a value of 1.

The process of combining maps to create a suitability map involves merging multiple raster layers that have been assigned binary values indicating suitability (0 for unsuitable, 1 for suitable). This integrated map highlights regions based on their overall appropriateness for specific uses, such as site selection for solar photovoltaic power plants. Each layer's information contributes to a composite view that assists decision-makers in identifying optimal locations. Zonal statistics is a spatial analysis technique used to evaluate the potential for photovoltaic energy within specified administrative areas. By applying this method, we can calculate statistics like the mean values of raster cells within each zone. The final results are visualised using a thematic map in GIS.

3. Results and discussion

By conducting a thorough geoinformation assessment, suitable locations for solar plant development in the Ivano-Frankivsk region were identified. Generally, areas with slope up to 3°, solar radiation more than $1100kWhm^-2$ per year, distance from the power lines up to 1000 m and average temperature in July between 25°C and 15°C, were evaluated as the most suitable for the construction of solar plants [14, 32].

The photovoltaic potential of the territories was estimated based on the expected land capacity of 0.003-0.004 ha/kW [8, 33] and the territorial communities were categorized into six groups based on their photovoltaic potential (figure 3).

For communities with the highest potential (above 25 MW), the areas were estimated with an equal interval classification method according to the following five categories:

- the most suitable areas;
- high suitability;
- moderate suitability;
- low suitability;
- not suitable at all.
- zonal statistic – assessing administrative areas photovoltaic potential;
- thematic cartography and visualisation.

The results are shown in table 1.

There are two major limitations in this study that could be addressed in future research. First, the study focused on large-scale assessment and did not take into account small-scale photovoltaic installations that could be situated on private properties, rooftops, or facades of individual buildings [34–37]. Second, access to information resources with spatial data, including the Public Cadastral Map, is currently limited due to the restrictions of martial law in Ukraine. Therefore, it is not possible to compare the compliance of identified sites suitable for solar plant location with plots designated as 'lands for industry, transport, communications, energy, defence and other purposes'.

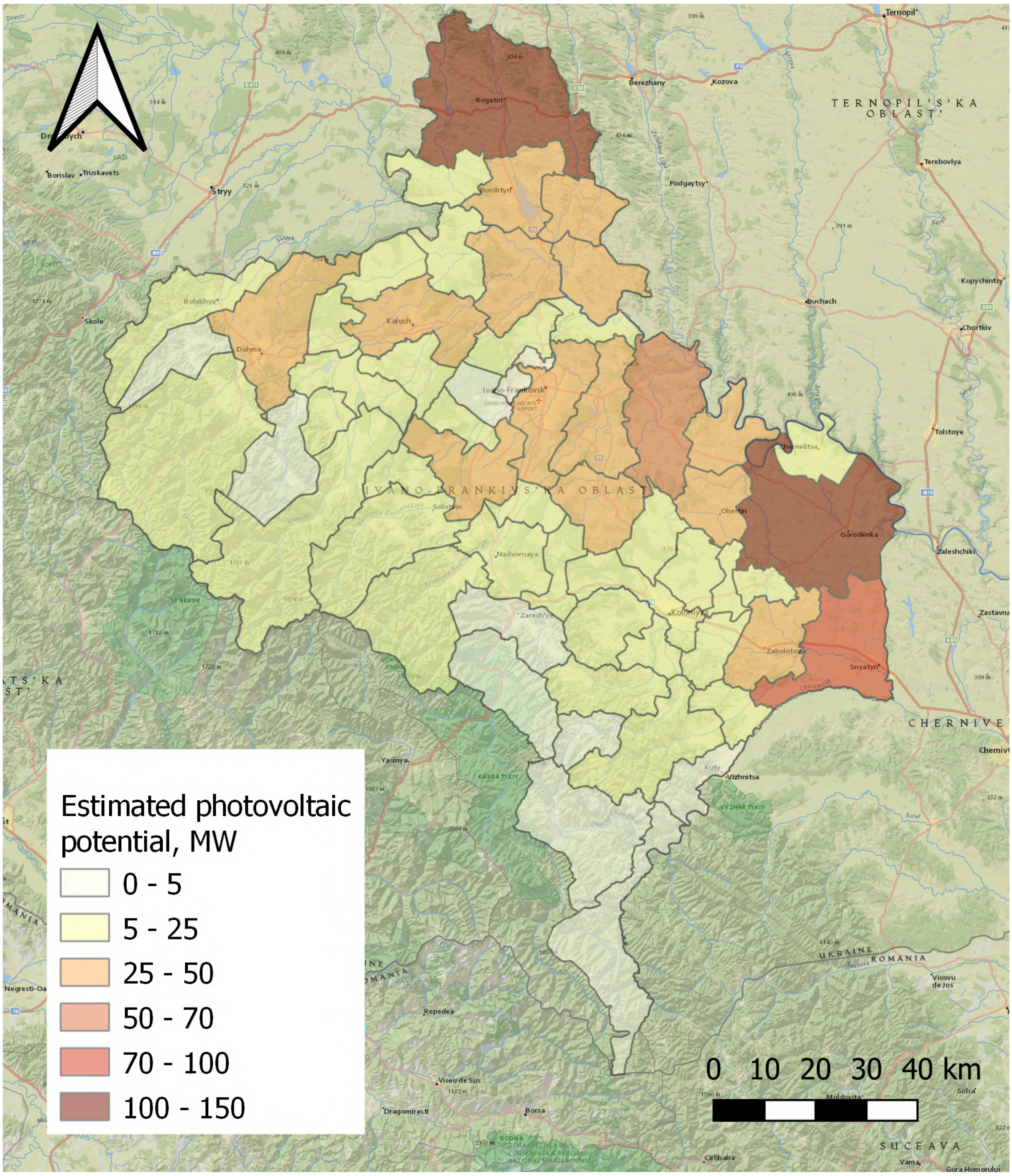

Figure 3. Photovoltaic potential of the communities within Ivano-Frankivsk region.

4. Conclusions

The sustainable reconstruction of Ukraine's energy system faces obstacles due to the ongoing war, widespread destruction, a substantial dependence on fossil fuels, and hindered advancements toward climate goals. The loss of solar energy capacities in the south of Ukraine makes it necessary to focus on the western regions, the solar potential of which is significantly lower due to natural factors. Therefore, geoinformation systems, which allow for an effective and

Table 1. Communities with the highest photovoltaic potential.

Community	The most suitable areas, km^2	High suitability, km^2	Moderate suitability, km^2	Low suitability, km^2	Unsuitable areas, km^2
Horodenkivska	105	144	69	11	295
Rohatynska	70	114.5	55.5	17.5	390.5
Snyatynska	84	71	19.5	2	177.5
Tlumatska	48.5	61.5	22.5	6	220.5
Ivano-Frankivska	67	38	6.5	0.5	149
Tysmenytska	37	41.5	15	5.5	152
Zabolotivska	39	39	17	4	125
Bohorodchanska	35.5	33	8.5	6	167
Kaluska	48	35	4	0.5	185.5
Obertynska	31.5	40.5	11.5	2	75.5
Burshtynska	32.5	37.5	9	4	119
Bilshyvtsivska	22.5	42.5	16.5	1	71.5
Otyniyska	26	36.5	12	1.5	122
Halytska	35	29	8.5	1.5	165
Dolynska	35	31.5	11.5	2	293
Oleshanska	24.5	29.5	9	2	92
Dubovetska	25	24.5	13.5	3.5	110.5

comprehensive assessment of the potential for placing solar energy facilities, are an indispensable tool for spatial planning at both the regional and local levels. The creation of assessment cartographic models of solar potential at the local communities' scale will make it possible to create cadastres of solar potential in the future to improve land management in the Ivano-Frankivsk region. The study identified the territorial communities with the highest potential for the installation of solar power plants, namely Horodenkivska, Rohatynska and Snyatynska. The territorial communities with the lowest potential are those with a high level of urbanisation and located in mountainous areas. Obviously, for these communities it is worth considering the possibility of installing solar panels on individual buildings. As the future development of the research is considered the development of an integration roadmap for integrating solar power into the existing energy framework of the region. This plan will address technical, economic, and regulatory aspects, ensuring that the transition to solar energy is smooth and sustainable. It will also include strategies for scaling up solar energy production, integrating it with other forms of renewable energy, and possibly achieving sustainability and energy independence.

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Increase in the energy efficiency of the biogas production process through vibration activation of heat and mass exchange processes in the bioreactor

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Increase in the energy efficiency of the biogas production process through vibration activation of heat and mass exchange processes in the bioreactor

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Abstract. One of the important problems preventing the increase in energy efficiency of biogas reactors is the use of heating elements operating in the free-convective mode of heat exchange. In addition to the large heat exchange areas, and the correspondingly reduced useful volume of the reactor, the use of free convective heat exchangers leads to the formation of stagnation zones, stratification of the medium, hypocooling of the lower zones of the reactor, overheating of the upper zones. The intensification of the heat exchange between the heating element and the substrate will allow to reduce the area of the heat exchange devices in the reactor, activate the thermostabilizing processes and reduce the cost of the reactor construction. Based on the results of the analysis of the influence of the fluid oscillation created by the movement of the activator plate on the intensity of heat transfer from the heating wall to the water and the substrate, the choice of the determining temperature of the liquid and the temperature of the wall with different methods of organizing convection is substantiated.

1. Introduction

The profitability of biogas plants is inversely proportional to the energy consumption for heating the reactor. Microbiological features of the anaerobic fermentation process require compliance with the limits of temperature regimes and temperature stabilization, uniform heating of the environment, absence of hypothermic and overheating zones.

In paper [1] is investigated the phenomena of biogas production and mass transfer for individual anaerobic granules in a microreactor.

A thorough examination of biogas production performance in both submerged and external Anaerobic Membrane Bioreactors featuring polymeric and ceramic membranes is conducted by Tomczak et al. [2]. The study places particular emphasis on analyzing the influence of temperature and hydraulic retention time on biogas yield. Additionally, detailed descriptions of strategies to mitigate fouling are provided.

In [3] is formed a neural network model of the investment process of biogas production, which allows to increase the efficiency of the management decision-making process on the feasibility of investing in biogas plants.

Terziev, Zlateva and Ivanov [4] considers enhancing the fermentation process in the digester for biogas production, obtained from animal and plant waste substrates.

Pilarski et al. [5] analyze energy conversion in an active biogas plant as an open thermodynamic system.

Abanades et al. [6] provide a brief overview of some safety rules and proposed policies based on world regulations. The effect of these regulations and policies on marketing and promoting biogas is highlighted for different countries.

In the course of anaerobic fermentation of biomass, it is necessary to observe certain limits of temperature regimes [7–14]:

- psychrophilic – substrate temperature up to 20°C, fluctuations ± 3...4°C;
- mesophilic – substrate temperature 35°C, fluctuations ± 2.8°C;
- thermophilic – substrate temperature 55°C, fluctuations ± 0.3°C.

At the same time, the speed of movement of the substrate under the conditions of the optimal fermentation process should not exceed 0.7 m/s. The expansion of the development of biogas plants requires a reduction in their capital and operating costs.

One of the important problems preventing the increase in energy efficiency of biogas reactors is the use of heating elements operating in the free-convective mode of heat exchange. In addition to the large heat exchange areas, and the correspondingly reduced useful volume of the reactor, the use of free convective heat exchangers leads to the formation of stagnation zones, stratification of the medium, hypocooling of the lower zones of the reactor, overheating of the upper zones. The intensification of the heat exchange between the heating element and the substrate will allow to reduce the area of the heat exchange devices in the reactor, activate the thermostabilizing processes and reduce the cost of the reactor construction.

2. Results and discussion

In literary sources, the following methods of intensification of free-convective heat exchange under the conditions of external washing of the surface are of interest [7, 11–14]:

1) the formation of a forced flow near the heating surface due to the installation of vertical limiting walls;
2) increasing the heat exchange surface by finning, which can both increase and decrease the intensity of heat exchange;
3) local and massive bubbling of the heat exchange surface by biogas jets, while the intensity of heat exchange increases by 1.5...2.0 times;
4) vibration of the heat exchange surface, which increases the intensity of heat transfer for water up to 20 times, but it is undesirable due to structural complications of the heat supply and vibration drive systems;
5) vibration of the environment, acoustic methods, the maximum achievable intensification of heat exchange 2...4 times.

The method based on the vibration of the environment is the most suitable for the conditions of the biogas plant, since, in addition to the intensification of heat transfer, additional mixing takes place. Also, among the most effective methods of increasing the intensity of heat exchange when liquid flows around bodies is the vibration of the environment, which provides, under optimal conditions, an increase in the intensity of heat exchange by 2-4 times compared to free convection. The high intensity of heat exchange during the vibration of the medium and the relatively small consumption of power for its implementation, the simplicity and flexibility of managing this process – all this provides the advantages of vibration activation in relation to other ways of intensifying heat exchange in liquids and gases. These advantages have led to a fairly widespread of vibration activation in modern technology. Washing surfaces with liquid waves is used in power engineering, metallurgy, chemical technology, air conditioning systems, and other fields of technology.

Oscillation of the liquid with the help of a pulsator-valve, a crank mechanism, etc. allows to create of artificial turbulence in the area of the heat exchange surface, which will destroy the viscous wall layer, intensive washing of the heating wall and intensification of heat exchange. For small and medium-sized reactors, one of the effective mechanisms for stirring is the engine-driven crank-rod stirrer. Consider the movement of the crank mechanism, which was used as a pulsation exciter in the biogas reactor (figure 1). Let's assume that the mechanism activates the activator plate, which is placed above the heat exchanger and performs oscillating movements above it. The plate can be both solid and perforated, its shape determines the hydraulic resistance of the medium – the substrate.

The equation of motion of the activator plate can be found by solving the Lagrange equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \phi}\right) - \frac{\partial T}{\partial \phi} = Q\phi, \tag{1}$$

The total kinetic energy of the system is defined as the sum of the kinetic energies of the movement of the components of the crank-connecting mechanism – the flywheel, the crank and the activator plate:

$$T = T_1 + T_2 + T_3, \tag{2}$$

To determine the kinetic energies of the components of the system, we write down the kinematic relations between the elements.

Having entered the coordinate system, as shown in figure 1, we write down the kinematic relations between the components of the activator mechanism and the velocity equation, provided that the instantaneous center of velocity is point P_2.

$$KA = r \cdot \sin(\phi) - \epsilon, \tag{3}$$

$$KB = \sqrt{l^2 - (\sin(\phi) - \epsilon)^2}. \tag{4}$$

$$\left\{ \begin{array}{r} Y_B = r \cdot \cos(\phi) + KB \\ X_B = \epsilon \end{array} \right\} \tag{5}$$

$$\left\{ \begin{array}{r} X_c = \epsilon + \frac{\mathrm{K}A}{2} = \epsilon + (r \cdot \sin(\phi) - \epsilon)/2 \\ Y_c = r \cdot \cos(\phi) + \frac{\mathrm{K}B}{2} = r \cdot \cos(\phi) + 0.5 \cdot \sqrt{(l^2 - (r \cdot \sin(\phi) - \epsilon)^2)} \end{array} \right\} \tag{6}$$

$$\left\{ \begin{array}{r} V_B = \dot{Y}_B = \dot{\epsilon} * r * \sin(\phi) + \frac{-(r * \sin(\phi) - \epsilon) \cdot r \cdot \cos(\phi) \cdot \dot{\phi}}{\sqrt{l^2 - (r \cdot \sin(\phi) - \epsilon)^2}} \\ V_C = \sqrt{\dot{X}_c^2 + \dot{Y}_c^2} = -\sqrt{\frac{r^2 \cdot \dot{\phi}^2 \cdot \cos^2(\phi)}{4} + \left| -r \cdot \dot{\phi} \cdot sin(\phi) - \frac{\dot{\phi} \cdot r \cdot cos(\phi) \cdot (r \cdot sin(\phi) - \epsilon)^2}{\sqrt{l^2 - (r \cdot \sin(\phi) - \epsilon)^2}} \right|} \end{array} \right\} \tag{7}$$

The distance h_2, which will be covered by the center of mass of the link PK – point C, during the movement of the mechanism, is determined according to the equation:

$$h_2 = r + \sqrt{l^2 - \epsilon^2}/2 - \left(r \cdot \cos(\phi) + \sqrt{l^2 - 0.5 \cdot (r \cdot \sin(\phi) - \epsilon)^2}\right), \tag{8}$$

The distance h_3 passed by point B during movement of the mechanism is determined from the equation:

$$h_3 = r + \sqrt{l^2 - \epsilon^2} - \left(r \cdot \cos(\phi) + \sqrt{l^2 - (r \cdot \sin(\phi) - \epsilon)^2}\right), \tag{9}$$

Let's find the equation describing the value of the generalized force Qϕ:

$$Q_\phi = \frac{\delta A}{\delta \phi}. \tag{10}$$

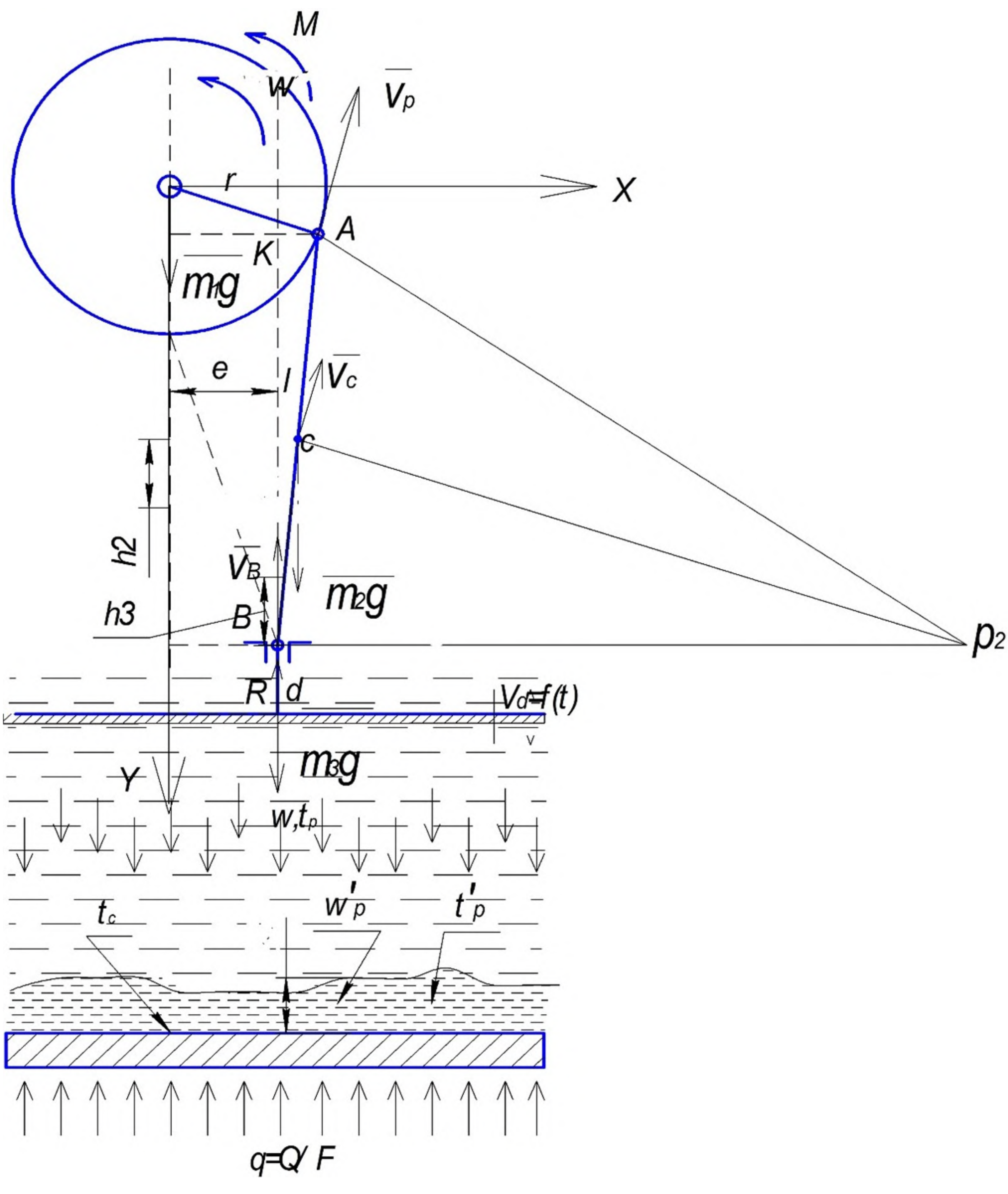

Figure 1. Dynamic diagram of the movement of the working organ of the bioreactor with an activator plate.

The total work of the forces acting on this activator mechanism consists of the work of the weight of the crank link – A_m2g weight forces of the slider $-A_m3g$; work moment of forces, which sets the activator in motion – A_M; the work of the resistance force of the movement medium of the activator plate is A_R.

$$A = A_m2g + A_m3g + A_M + A_R \tag{11}$$

Let's find the meaning of these works:

$$A_m 2g = -m_2 \cdot g \cdot \left[r \cdot (1 - \cos(\phi)) + \frac{\sqrt{(l^2 - \epsilon^2) - \sqrt{(l^2 - (r \cdot \sin(\phi) - \epsilon)^2)}}}{2} \right] \tag{12}$$

$$A_m 3g = -m_2 \cdot g \cdot \left[r \cdot (1 - \cos(\phi)) + \sqrt{(l^2 - \epsilon^2)} - \sqrt{(l^2 - (r \cdot \sin(\phi) - \epsilon)^2)} \right] \tag{13}$$

$$A_M = M \cdot \phi \tag{14}$$

We write down the resistance force of the movement medium of the activator plate in the form:

$$R = C \cdot S \cdot \frac{\rho \cdot Wmax^2}{2} \tag{15}$$

where C is the experimental coefficient [15], which depends on the aspect ratio of the plate; $Wmax$ is the maximum permissible speed of movement of the substrate ($Wmax = 0.7$ m/s). Using the value of the resistance of the medium in the form (15) allows us to take into account only the technologically maximum permissible value of the speed of movement of the substrate, thus simplifying the engineering solution of equation (1).

$$A_R = -0.245 \cdot m_3 \cdot \rho \cdot C \cdot S \cdot \left(r + \sqrt{(l^2 - \epsilon^2)} - (1 \cdot \cos(\phi) + \sqrt{(l^2 - (r \cdot \sin(\phi) - \epsilon)^2)} \right) \tag{16}$$

Then the expression for finding the generalized force will have the form:

$$\begin{aligned} Q = M - m_2 \cdot g \cdot \left(r \cdot \sin(\phi) + \frac{\cos(\phi) \cdot (r \cdot \sin(\phi) - \epsilon)}{2 \cdot \sqrt{l^2 - (r \cdot \sin(\phi) - \epsilon)^2}} \right) - m_3 g \cdot \\ -m_3 g \cdot \left[r \cdot \sin(\phi) + \frac{r \cdot \cos(\phi) \cdot (r \cdot \sin(\phi) - \epsilon)}{2 \cdot \sqrt{l^2 - (r \cdot \sin(\phi) - \epsilon)^2}} \right] - \\ -0.245 \cdot m_3 \cdot \rho \cdot C \cdot S \cdot \left(r + \sqrt{(l^2 - \epsilon^2)} - (r \cdot \cos(\phi) + \sqrt{(l^2 - (r \cdot \sin(\phi) - \epsilon)^2)} \right) \end{aligned} \tag{17}$$

The kinetic energy of the system is the sum of the kinetic energies of the component links. Taking into account the peculiarities of the movement of each of the components, we will write down the equation for determining the kinetic energies of the links of the oscillatory activator:

$$T = T_1 + T_2 + T_3 \tag{18}$$

The kinetic energy of the first body is rotational motion:

$$T_1 = \frac{J \cdot \dot{\phi}^2}{2} = \frac{m_1 \cdot r^2 \cdot \dot{\phi}^2}{4} \tag{19}$$

The kinetic energy of the second body is plane-parallel motion:

$$\begin{aligned} T_2 = \dot{\phi} \cdot r^2 \cdot m_2 \cdot 0.5 \left[\left[\frac{\left[r \cdot \cos(\phi) + \sqrt{[l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \cdot \tan(\phi) - \epsilon \right]^2}{l^2 - (r \cdot \sin(\phi) - \epsilon)^2} \right] + \right. \\ +0.25 \cdot l^2 - \left[r \cdot \cos(\phi) + \sqrt{[l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \cdot \tan(\phi) - \epsilon \right] \cdot \\ \left. \cdot (r \cdot \sin(\phi) - \epsilon) + \frac{l^2}{12 \cdot [l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \right] \end{aligned} \tag{20}$$

The kinetic energy of the third body is translational motion

$$T_3 = \phi^2 \cdot r^2 \cdot \left[\frac{m_3 \left[(r-\epsilon)\cos(\phi) + \left[l^2 - (r \cdot \sin(\phi) - \epsilon)^2 \right]^2 \right]}{2 \cdot (\cos(\phi))^2 \cdot [l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \right] \tag{21}$$

The expression for determining the kinetic energy will look like this:

$$\begin{aligned} T = \phi^2 \cdot r^2 \cdot \Bigg[& 0.25 m_1 + \frac{m_3 \left[(r-\epsilon)\cos(\phi) + \left[l^2 - (r \cdot \sin(\phi) - \epsilon)^2 \right] \right]^2}{2 \cdot (\cos(\phi))^2 \cdot [l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} + \\ & + m_2 \cdot 0.5 \left[\left[\frac{r \cdot \cos(\phi) + \sqrt{[l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \cdot \tan(\phi) - \epsilon^2}{(l^2 - (r \cdot \sin(\phi) - \epsilon)^2)} \right] + \right. \\ & + 0.25 \cdot l^2 - \left[r \cdot \cos(\phi) + \sqrt{[l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \cdot \tan(\phi) - \epsilon \right] \cdot \\ & \left. \cdot (r \cdot \sin(\phi) - \epsilon) + \frac{l^2}{12 \cdot [l^2 - (r \cdot \sin(\phi) - \epsilon)^2]} \right] \Bigg] \end{aligned} \tag{22}$$

The partial derivative of the kinetic energy along the angle of rotation:

$$\begin{aligned} \frac{\delta T}{\delta \phi} = (& m_3^2 \cdot \frac{\left[(r-e) \cdot \cos(\phi) + l^2 - (r \cdot \sin(\phi) - e)^2 \right]}{\cos(\phi)^2 \cdot [l^2 - (r \cdot \sin(\phi) - e)^2]} \cdot \\ & \cdot [(-r-e) \cdot \sin(\phi) - 2(r \cdot \sin(\phi) - e) \cdot r \cdot \cos(\phi)] + \\ & + m_3^2 \cdot \frac{\left[(r-e) \cdot \cos(\phi) + l^2 - (r \cdot \sin(\phi) - e)^2 \right]^2}{\cos(\phi)^3 \cdot [l^2 - (r \cdot \sin(\phi) - e)^2])} \cdot \sin(\phi) + \\ & + m_3^2 \cdot \frac{\left[(r-e) \cdot \cos(\phi) + l^2 - (r \cdot \sin(\phi) - e)^2 \right]^2}{\cos(\phi) \cdot [l^2 - (r \cdot \sin(\phi) - e)^2]} \cdot (r \cdot \sin(\phi) - e) \cdot r + \\ & + 0.5 \cdot m_2 \cdot \Bigg[2 \cdot \frac{[r \cdot \cos(\phi) + [l^2 - (r \cdot \sin(\phi) - e)^2]^1/2 \cdot \tan(\phi) - e]}{l^2 - (r \cdot \sin(\phi) - e)^2} \cdot \\ & \cdot [-r \cdot \sin(\phi) - \frac{1}{[l^2 - (r \cdot \sin(\phi) - e)^2)]^1/2} \cdot \tan(\phi) \cdot (r \cdot \sin(\phi) - e) \cdot \\ & \cdot r \cdot \cos(\phi) + [l^2 - (r \cdot \sin(\phi) - e)^2]^1/2 \cdot (1 + \tan(\phi)^2] + \\ + 2 \cdot & \frac{[r \cdot \cos(\phi) + [l^2 - (r \cdot \sin(\phi) - e)^2]^1/2 \cdot \tan(\phi) - e]^2}{l^2 - (r \cdot \sin(\phi) - e)^2} \cdot (r \cdot \sin(\phi) - e) \cdot r \cdot \cos(\phi) - \\ & - [-r \cdot \sin(\phi) - \frac{1}{[l^2 - (r \cdot \sin(\phi) - e)^2)]^1/2} \cdot \tan(\phi) \cdot (r \cdot \sin(\phi) - e) \cdot \\ & \cdot r \cdot \cos(\phi) + [l^2 - (r \cdot \sin(\phi) - e)^2]^1/2 \cdot (1 + \tan(\phi)^2] \cdot (r \cdot \sin(\phi) - e) - \\ & - [r \cdot \cos(\phi) + [l^2 - (r \cdot \sin(\phi) - e)^2]^1/2 \cdot \tan(\phi) - e] \cdot r \cdot \cos(\phi) + \\ & + \frac{l^2}{[12 l^2 - 12(r \cdot \sin(\phi) - e)^2)]^2} \cdot (r \cdot \sin(\phi) - e) \cdot r \cdot \cos(\phi) \Bigg] \cdot \phi^2 \cdot r^2 \end{aligned} \tag{23}$$

In (22), we denote the expression in parentheses by "D", then the time derivative:

$$\frac{d}{dt} \left(\frac{\delta T}{\delta \dot{\phi}} \right) = 2 \cdot \ddot{\phi} \cdot r^2 \cdot D \tag{24}$$

The Lagrange equation (1) will be written in the form:

$$2 \cdot \ddot{\phi} \cdot r^2 \cdot D - \frac{\delta T}{\delta \phi} = Q_\phi, \tag{25}$$

where $\delta T/\delta\phi$ and Q_ϕ are determined from equations (23) and (17), respectively. Let's turn the resulting nonlinear differential equation into a system of linear differential equations of the first order by substitution:

$$\begin{bmatrix} \ddot{\phi} = \dot{z} \\ \dot{\phi} = z \end{bmatrix} \tag{26}$$

We will solve this system using the Runge–Kutta numerical method and obtain a solution in the form of values of the function $\omega = f(\varphi)$. Using the solution of system (26), it is possible to determine the value of the speed of the activator plate. The liquid under the action of the plate also begins to make oscillatory movements and washes the heat exchange surface. A wall layer is located around the heat exchange surface, in which heat is transferred mainly due to thermal conductivity (figure 2).

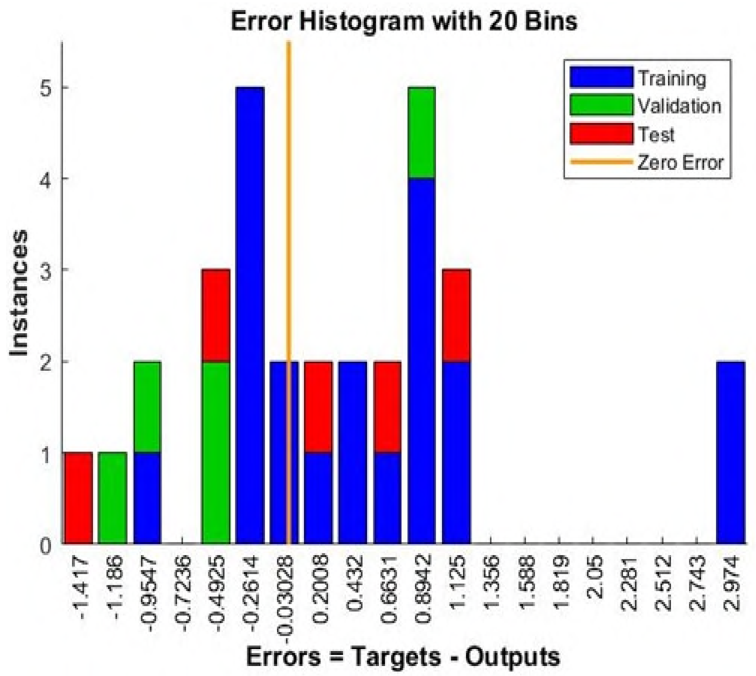

Figure 2. Thermal and hydrodynamic situations around the heat exchange surface according to the hypothesis of Reynolds and Prandtl.

According to the Fourier equation, we write that the heat flow q is determined:

$$q = \lambda \cdot \frac{t'_p - t_c}{\delta'_t} \tag{27}$$

where δ'_t is the thickness of the thermal layer; t'_p is the temperature of the liquid in the wall layer.

According to Kays, Crawford and Weigand [16], and Bergman et al. [17] the thickness of the viscous wall hydrodynamic δ' and thermal δ'_t layers is determined from the dependencies:

$$\delta' \approx 12 \frac{\nu}{\sqrt{s/\rho}} \tag{28}$$

$$\delta'_t \approx 12\frac{\nu Pr^{-0.33}}{\sqrt{s/\rho}} \tag{29}$$

The thermophysical properties of the substrate are determined from equations [7]:

$$\rho = 1000 + 2.4 \cdot c; \tag{30}$$

$$c_p = c_{dry} \cdot c + c_w \cdot (1 - c); \tag{31}$$

$$\mu = \mu_w \cdot \left[1 + 10 \cdot \left(\frac{10 \cdot (c-2)}{(11 - \beta_u \cdot c)} + c\right)\right], \tag{32}$$

where c is the content of dry matter, 2–15%; c_{dry} - heat capacity of the dry substance of the substrate; c_w – heat capacity of water; μ_w is the viscosity of water at a certain temperature; β_u is a coefficient that depends on the type of waste and is 0.7 ... 0.75 for cattle and β_u =0.6...0.7 for pigs.

According to Newton's equation, the value of the tangential stress is defined as:

$$s = \mu_w \frac{w'}{\delta'} = \mu_w \cdot \left[1 + 10 \cdot \left(\frac{10 \cdot (c-2)}{(11 - \beta_u \cdot c)} + c\right)\right] \cdot \frac{w'}{\delta'}, \tag{33}$$

where w' is the speed of movement of substrate particles that have entered the wall layer.

According to the Reynolds theory, supplemented by Prandtl hypothesis, the fluid flow washing over the heat exchange surface and having an average speed w, falling into the wall layer, slows down and acquires a speed w'. The temperature of the liquid inside the flow is t_p, the temperature of the liquid inside the wall layer is t'_p. According to the law of conservation of momentum, the force of motion resistance will have the form:

$$S = G' \cdot (w - w'), \tag{34}$$

where G' is the amount of liquid that entered the wall layer per unit of time. The amount of heat transferred by the liquid G' will be determined according to the expression:

$$Q = G' \cdot c_p \cdot (t_p - t'_p) \tag{35}$$

Then, given that S $= s \cdot F$ and Q$= q \cdot F$, we get:

$$q = c_p \cdot s \cdot \frac{t_p - t'_p}{w - w'} \tag{36}$$

From equations (29) and (33), the velocity in the wall layer w$'$ is determined:

$$w' = 12\sqrt{s/\rho} \tag{37}$$

Temperature gradients are determined from equations (27) and (35).

$$t'_p - t_c = q \cdot \delta'_t/\lambda \tag{38}$$

$$t_p - t'_p = \frac{q \cdot (w - w')}{c_p \cdot s} \tag{39}$$

Adding expressions (38) and (39), we get:

$$t_p - t_c = \frac{q \cdot (w - w')}{c_p \cdot s} + q \cdot \delta'_t/\lambda \tag{40}$$

Let's transform equation (40), taking into account that

$$\alpha = \frac{q}{t_c - t_p}$$

$$\alpha = \left[\frac{w - 12\sqrt{s/\rho}}{c_p \cdot s} + \frac{12\upsilon}{\lambda\sqrt{s/\rho}} \right]^{-1} \tag{41}$$

The values of isobaric heat capacity, density, and viscosity can be determined using equations (30), (31), (32).

The speed of fluid movement w is determined from the solution of system (26), assuming that the fluid moves to the heat exchange surface at the speed of movement of the activator plate. In the criterion form, equation is written as:

$$Nu = \frac{d}{\lambda} \left[\frac{w - 12\sqrt{s/\rho}}{c_p \cdot s} + \frac{12\upsilon}{\lambda\sqrt{s/\rho}} \right]^{-1} \tag{42}$$

The value of the tangential stress s during vibration washing of a single cylindrical surface is currently unknown. In the first approximation, it is possible to take the value of the tangential stress determined for the turbulent washing of the plate, transforming it as follows:

$$s = 0.037 \cdot \rho \cdot \frac{(w_A)^2}{2} \cdot (w_a \cdot d/2 \cdot \upsilon)^{-0.2} \tag{43}$$

Thus, equation (42) makes it possible to determine the value of the Nusselt criterion during oscillatory washing of the heat-exchange cylindrical surface in bioreactors for the utilization of organic waste of agricultural enterprises.

Based on the results of the analysis of the developed mathematical model, it has been found that in the range of measurements, the obtained value of the increase in the coefficient of heat transfer from the horizontal heating tubular element to the water exceeds the value for free convection by an average of 1.5...2.8 times. Both medium fluctuations and heat flow have a significant influence on the intensification of heat exchange. Moreover, an increase in the frequency of oscillations affects the increase in the coefficient of heat transfer from the horizontal cylinder to the water more significantly than an increase in the amplitude by an average of 15–25%. After analyzing equation (43), the surface of the influence of the arguments included in this equation – R_e and P_r – on the value of the function – the Nusselt criterion (figure 3) was constructed.

The proposed mathematical model calculates the heat exchange processes in biogas reactors under vibration activation of the substrate heating process from the tubular heat exchange element. Based on the parameters of the heat exchange subsystem of the reactor: the heat exchange area, the frequency and amplitude of oscillations, the temperature of the coolant, the thermophysical properties of the substrate, choosing one of the three fermentation temperature regimes, it is possible to determine the heat exchange coefficient from the surface of the heater to the substrate, calculate the amount of heat transferred, carry out design calculations of the heat exchange process. In addition to activating heat exchange processes in the substrate environment, temperature fields are equalized, and warming is more uniform.

Due to the activation of the heat exchange, a reduction in the mass of the heat exchange process for the $V = 3$ m^3 reactor was achieved by 18% a decrease in the cost of the reactor by 7% due to a lower cost of the heat exchange process (while taking into account the increase in the price of the reactor due to the vibration activator), an increase in the yield of biogas due to thermal stabilization by 12...14% compared to the free convective heating process. The results were obtained at a model reactor and as a result of implementation in a small farm in the Vinnytsia region.

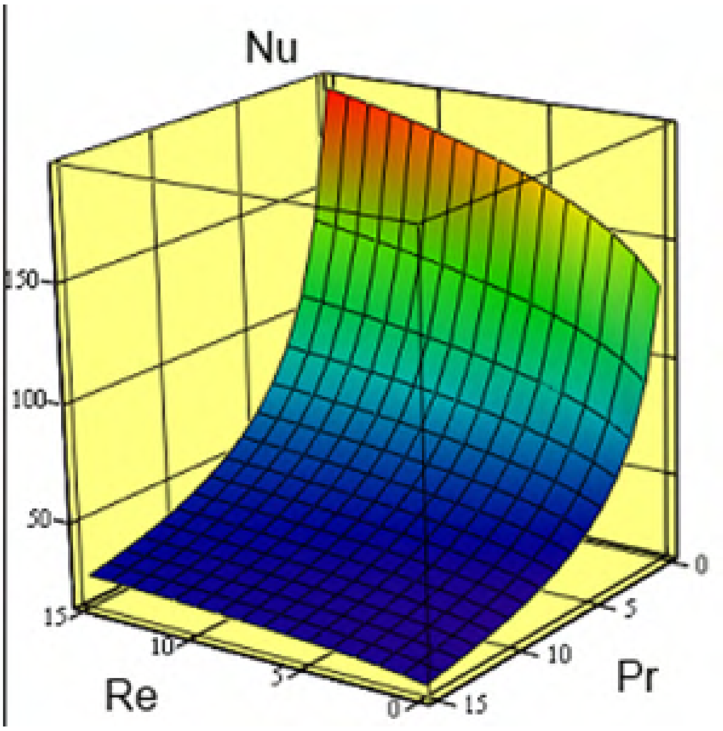

Figure 3. The surface of the influence of the Reynolds and Prandtl criteria on the value of the Nusselt criterion during vibration activation of heat exchange.

3. Conclusions

The law of motion of the activator plate has been found by solving Lagrange's differential equation. Based on the laws of thermal conductivity, convective heat and mass transfer, and conservation of momentum, a criterion equation has been developed that describes the heat exchange processes between the heating element and the substrate during oscillatory washing of the heater wall.

The mathematical model was checked for adequacy by comparing the obtained results with the results of experimental studies. For this, several experimental data were collected. Based on the comparison of two samples using the Student's criterion, the model was evaluated, errors were calculated, and a t-test was performed. It was determined that the t value does not exceed the critical value for the given degrees of freedom and the significance level of 0.05. That is, the developed mathematical model is adequate.

Based on the results of the analysis of the influence of the fluid oscillation created by the movement of the activator plate on the intensity of heat transfer from the heating wall to the water and the substrate, the choice of the determining temperature of the liquid and the temperature of the wall with different methods of organizing convection is substantiated. It has been found that the oscillation of the medium by the activator plate intensifies the free convective heat transfer in the aqueous medium by 1.5...3.0 times, in the $C = 8\%$ suspension by 1.3...2.5 times. Thus, the use of an activator plate to intensify heat exchange in bioreactors allows thermostabilization and intensification of the biogas production process and saves material resources by reducing the area of heat exchange devices.

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Improved the municipal wastewater treatment technology in towns and villages

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Improved the municipal wastewater treatment technology in towns and villages

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Abstract. Traditional biological wastewater treatment systems are unable to completely remove biogenic substances due to the lack of the necessary amount of substrate, the specifics of the technological scheme, and only the involvement of raw sediment and partially excess sludge in the biological process (continued aeration) can solve the specified problem. The use of psychrophilic anaerobic displacement reactors with an expanded layer of sludge (EGSB-reactors) and subsequent stages of biological treatment will allow to achieve of deep purification of wastewater from carbon, nitrogen and phosphorus in purified water and significantly reduce the volume of extracted sediments and their morphology. Therefore, the aim of our work was the development of a method of municipal wastewater treatment using facilities with a lower material capacity, with lower energy consumption for deep biological removal of carbon, nitrogen and phosphorus compounds. Systematic investigations of the technologies, reactor designs, and processes for anaerobic treatment of low-concentration effluents in psychrophilic conditions calculations were carried out at the Kaniv wastewater treatment plant. Based on this, a model-concept of treatment facilities was developed. Design work was completed for the reconstruction of the Kaniv wastewater treatment plant, where two EGSB psychrophilic reactors, converted from the existing two-tier clarifiers, were put into operation.

1. Introduction

Pollution of rivers with untreated sewage, which are sources of drinking water, and significant areas adjacent to treatment plants with waste from cleaning (sediment) is an urgent problem today [1–4]. For example, the annual environmental damage caused to the environment by inefficiently working facilities with a capacity of 1.0 thousand m^3/day (Hadyach, Poltava region – 2020-2021) is estimated at UAH 8.0 million, excluding additional costs to water intakes located downstream, to bring drinking water to the requirements of Sanitary rules and norms [5]. There are more than a hundred such structures in Ukraine. No one has calculated the losses from the global pollution of large and medium-sized rivers by discharges of untreated or insufficiently treated sewage from small cities and towns in Ukraine, but, in our opinion, they are extremely large if all the consequences are taken into account.

Most of the municipal sewage treatment plants in small towns and villages have long been physically worn out and require significant restoration work or new construction [6]. Also, the existing technologies for wastewater treatment and sediment disposal are morally outdated and do not meet modern requirements for the removal of organic carbon, nitrogen, phosphorus and waste management; as a result of aridization of the climate – blooming of ponds, pollution of underground sources of drinking water, deterioration of atmospheric air quality [7,8]. The well-known methods of removing excess nitrogen compounds are ensuring the modes of nitrification of ammonium by autotrophic producers and denitrification of nitrites and nitrates by heterotrophic reductants to molecular nitrogen [9, 10]. To remove phosphorus compounds in practice, chemical methods (reagents) and biological methods are used both due to the selection of special heterotrophic phosphorus-accumulating organisms (FAO) and without FAO [11]. The disadvantage of known systems for the removal of biogenic elements is their significant energy and resource consumption with insufficient efficiency of biological purification, especially from phosphorus compounds [11–14].

The task we set for ourselves was to develop a method of municipal sewage treatment using structures with a lower material capacity, with lower consumption of energy carriers for deep biological removal of carbon, nitrogen and phosphorus compounds.

2. Materials and methods

The Kaniv wastewater treatment plant (WWTP) was chosen as the basic experimental site.

Laboratory control of the operation of sewage treatment plants – measurement of pollution indicators – was carried out according to the approved methods of the State Committee of Ukraine on matters of housing and utilities [15]:

- Methodology for measuring the mass concentration of petroleum products – Governing normative document (GND) 01-05-2002.
- Methodology for measuring the mass concentration of iron – GND 02-05-2002.
- Methodology for measuring the mass concentration of suspended substances – GND 03-05-2002.
- Methodology for measuring the mass concentration of ammonium nitrogen – GND 04-05-2002.
- Methodology for measuring biological oxygen demand (BOD)– GND 05-05-2002.
- Methodology for measuring the mass concentration of nitrates – GND 06-05-2002.
- Methodology for measuring the mass concentration of nitrites – GND 07-05-2002.
- Methodology for measuring settling substances – GND 08-05-2002.
- Methodology for measuring the mass concentration of orthophosphates – GND 09-05-2002.
- Methodology for measuring permanganate oxidizability – GND 10-05-2002.
- Methodology for measuring of sediment density – GND 11-05-2002.
- Methodology for measuring of anionic synthetic surfactants – GND 12-05-2002.
- Methodology for measuring of dissolved oxygen – GND 13-05-2002.
- Methodology for measuring the mass concentration of chlorides – GND 14-05-2002.
- Methodology for measuring mass concentration of sulfates – GND 15-05-2002.
- Methodology for measuring of chemical oxygen demand (COD)– GND 16-05-2002.
- Methodology for measuring of ash content and hygroscopic moisture of sediments – GND 19-05-2002.
- Methodology for measuring sediment moisture – GND 20-05-2002.
- Methodology for measuring total nitrogen – GND 23-05-2002.
- Methodology for measuring total phosphorus – GND 26-05-2002.

Ensuring the reliability of the determination of measurements according to the necessary indicators of pollution was carried out by the employees of the Institute through control checks. Also, the following approaches and calculations were used for express analytical assessment of organic pollution reduction:

- Biochemical consumption of oxygen during five days (BCO_5) = 0.875·BCO_{20} = 0.75·COC, where BCO_5 – biochemical consumption of oxygen during five days, BCO_{20} – biochemical consumption of oxygen during twenty days, COC – chemical oxygen consumption [16].
- Effect of sewage treatment on sand traps: for SS – 3-5 %; BCO – to 5 %, SS – suspended substances [17].
- COC (B) = 0.67·ASS; COC (B) – COC of active biomass [18].
- Cs = SS of anaerobic sludge, where Cs – sludge concentration [18].

For approximate calculations – COC (SS of raw sediment) = 0.98·SS according to [18] and COC = (BCO_{20} dark – BCO_{20} illumin.)/0.86 = 40.69 g/people·day, and SSsedim. = 40 g/people·day.

Lighting curves were obtained experimentally (according to [16, 19]).

Ultrasonic scanning of the reactor volumes and sludge sampling were carried out once a week during the maximum inflow of wastewater to the facilities and in the absence of wastewater. The break between the inflow of sewage to the sewage treatment plant (between measurements) was 15-20 minutes. Scanning was carried out with the Ease 245DS echo sounder, which has a depth scale displayed on the monitor, which allows continuous determination of the height of the silt. By changing the sensitivity of the device, the required effect of recognition of the silt layer was achieved. Checking the reliability of the device readings was determined by immersing the control board to a depth of 4 m from the water surface.

To determine the concentrations of sludge, its ash content and index, sludge from the expanded layer was taken by a submerged membrane pump of low productivity (domestic pump “Strumok”). The pump pumped out samples from different heights of the expanded layer.

The qualitative and quantitative composition of the formed gases was determined by the gas chromatography method. Gas chromatographic analysis of inorganic gases (H_2, CO, CO_2) 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 per min. The temperature of the columns thermostat and the detector is 100 ^oC, the evaporator temperature – 120 ^oC, 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 per min. Analysis temperature – 60 ^oC, evaporator temperature – 120 ^oC, 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 ^oC at a speed of 5 degrees per min. Samples were introduced into the column with a microsyringe with a capacity of 1.0 μl. Processing of the analysis results was carried out according to the areas of chromatographic peaks by the method of internal normalization using calibration coefficients.

3. Results and discussion

Systematic research was preceded by significant work on the study of technologies, reactor designs, and calculations of processes for anaerobic treatment of low-concentration effluents in psychrophilic conditions. Taking into account the economic situation in the communal economy of Ukraine, climatic conditions and the human factor, the existing projects and results of the operation of classical and experimental treatment facilities for small cities and settlements, as well as local treatment systems at individual enterprises, were rethought. Based on this, a model-concept of treatment facilities was developed, which provides for the following:

- replacement of primary clarifiers with anaerobic EGSB-reactors with an expanded layer of granular sludge;
- use for the aerobic stage of cleaning facilities with features of aerofilters with easy loading and aeration tanks-settlements;
- provision of conditions for constant removal of partially destroyed organic matter from the EGSB reactor to the next stage of purification;
- ensuring discharge of excess sludge from the aerobic treatment stage into the EGSB-reactor;
- application (based on the characteristics of the effluents) of the oxidation channel for additional purification of wastewater from nitrogen-containing compounds (nitrification);
- application (based on effluent characteristics) of a baffled anaerobic reactor (ABR) for effluent denitrification;
- the use of highly loaded sludge sites;
- application of jet aeration using submersible sludge pumps for deeper saturation of sludge with oxygen directly in the aerator.

The specified model-concept was applied during the implementation of design works for the reconstruction of Kaniv WWTP, where two EGSB psychrophilic reactors, converted from the existing two-tier clarifiers, were put into operation. The reactors were started without inoculant (a special biological preparation) and under a full hydraulic load, which was about 4 thousand m^3/day (of which almost 1.5 thousand m^3/day is the effluent of a local cheese factory). The formation of a trophic chain of anaerobes was assumed due to the introduction of microbial flora and fauna at the rate of 1 m^3 per 1000 m^3 of effluent. From the completion of the process of formation of the "working bacterial population" of the reactors to the first discharge of anaerobic surplus sludge from the EGSB reactors, six months passed, and the sludge discharged to the site had a moisture content of 90-92%. Over the next two weeks, it became air-dry and suitable for removal and transport.

The main task of the research, which would provide an understanding of the effective functioning of the creation of a wastewater treatment system, was to establish the characteristics of psychrophilic reactors for the treatment of households or equated to them wastewaters:

- volumetric load on the structure;
- load on sludge;
- the rate of removal of organic matter in an anaerobic reactor;
- total sludge increase;
- sludge concentration in the reactor;
- values of sludge expansion and sludge concentration limits;
- ashiness of silt and emerging crust;
- depth of destruction of suspended substances and excess sludge;
- sludge index.

The specified characteristics were determined by:

- carrying out laboratory control of wastewater treatment processes and destruction of settled organic suspended substances and excess sludge;
- organization of ultrasonic scanning of the volumes of anaerobic reactor structures in order to study the change in the height of the sludge to study its growth and the retention time of the biomass in the reactor;
- sampling sludge from the expanded layer during the recommended [18] of biomass retention time in the reactor and determination of concentrations, ash content and sludge age;
- analysis of daily (once a day), weekly (once a week) and average monthly indicators of pollution and sludge characteristics.

Sampling for laboratory analyses of pollution was carried out during the period of the maximum flow of sewage to treatment facilities, and for sludge – during the flow and in the absence of wastewater.

As an example, table 1 shows the results of laboratory-technological control of wastewater treatment in anaerobic psychrophilic reactors reduced to average monthly indicators.

Table 1: Results of laboratory-technological control of wastewater treatment in anaerobic psychrophilic reactors.

Wastewater characteristics	Control period in 2018			
	August	September	October	November
1. Inflow of sewage per day, m^3/day	3450	3510	3580	3690
2. Sewage treated per month, m^3/month	106950	105300	110980	110700
3. The effluents temperature at the entrance of buildings, ^oC	24.3	21.4	18.4	16.7
4. The effluents temperature at the outlet of the reactors, ^oC	23.8	19.6	17.3	16.1
5. Transparencies degree at the entrance of buildings, cm	0.5	0.4	0.5	0.4
6. Transparencies degree at the exit from the reactors, cm	2.4	2.4	2.2	2.3
7. Effluents pH at the entrance of buildings	7.61	7.63	7.68	7.75
8. Effluents pH at the outlet of the reactors	7.81	7.72	7.94	7.97
9. SS at the building's entrance, mg/dm^3	375	370	371	356
10. SS at the entrance of the reactor, mg/dm^3	290	283	285	272
11. Reduction of SS in sand traps (mineral and organic parts), mg/dm^3	85	87	86	84
12. Including the reduction of the organic part of SS – (from item 11), mg/dm^3	16	20	17	15
13. The equivalent of the reduction of the organic part of SS in COC (from item 12), mg/dm^3	15.7	19.6	16.7	14.7
14. Removed SS for sand platforms per month, kg/month	9090.8	9161.1	9544.3	9298.8
15. Pulp was unloaded on sludge sites per month (W=90%), m^3/month	91.0	92	95.4	93
16. SS at the outlet of the reactors, mg/dm^3	82	81	83	82
17. Reduction of SS in reactors, mg/dm^3	208	202	202	190
18. The equivalent of the reduction of SS in COC				

Table 1: Results of laboratory-technological control of wastewater treatment in anaerobic psychrophilic reactors.

Wastewater characteristics	Control period in 2018			
	August	September	October	November
in reactors, mg/dm^3	203.8	198	198	186.2
19. Removed SS in reactors per month, kg/month	22246	21271	22418	21033
20. Equivalent of SS in COC removed from reactors, kg/month	21796	20849	21974	20612
21. BCO_5 of easily degradable organic substances at the entrance of buildings, mg/dm^3	332.5	304	344	295
22. BCO_5 of easily degradable organic substances at the reactor inlet, mg/dm^3	317	289	326	283
23. BCO_5 of easily degradable organic substances at the outlet of reactors, mg/dm^3	215	191	220	189
24. COC of easily degradable organic substances at the entrance of buildings, mg/dm^3	456	405	440	391
25. COC of easily degradable organic substances at the reactor inlet, mg/dm^3	434	387	416	373
26. Reduction of COC in sand traps of easily degradable organic substances, mg/dm^3	22	18	24	18
27. COC reduction in the concentration of all organic pollutants in sand traps, mg/dm^3	37.7	37.6	40.7	32.7
28. COC of easily degradable organic substances at the outlet of the reactors, mg/dm^3	299	253	286	245
29. Reduction of COS of easily degradable organic substances in reactors, mg/dm^3	135	134	130	128
30. Reduction of COC in reactors of organic pollutants of various nature	338.8	332	328	314.2
31. Easily decomposable organic substances were removed from the reactors in one month	14438	14110	14427	14170
32. Easily decomposable organic substances removed from the reactors per period, kg/period	57145			
33. Extraction in reactors of easily decomposable organic substances per estimated day, kg/day	468.4 (40% of the extracted in reactors)			
34. Organic pollutants of various natures were removed from the reactors per month, kg/month	36234	34956	36401	34782
35. Removed from the reactors organic pollutants of various nature during the period, kg/period	142373			
36. Removal of organic pollutants of various nature in reactors per day, kg/day	1167			

The results of the scanning of the reactor volumes and the study of sludge from the expanded layer are summarized in table 2 and table 3 (monthly average indicators), where given the characteristics of sludge growth; sludge load; reduced rate of removal of organic matter in an anaerobic reactor; sludge concentrations; ash content of sludge; sludge index.

In the range of maximum flow velocities, which were determined by measuring inflows into the Parshall trough (for the reporting period – 1.13-1.38 m/h in the lighting zone), the expansion of the silt layer was 75-100 % (ultrasound scanning). The surface of the expanded silt did not have

Table 2. Results of scanning reactor volumes.

Characteristics	Control period in 2018			
	August	September	October	November
1. Removed from 1 reactor organic pollutants of various nature per month, kg/month	18117	17478	18201	17391
2. Removed from 1 reactor of organic pollutants before sludge discharge, kg	–	17478	35679	17391
3. The height of the expanded sludge layer at the end of the month, m	3.4	3.9	4.4	3.9
4. The volume of the expanded layer in one reactor, m^3	128	185	241	185
5. Sludge growth in the reactor before unloading, m^3	–	57	113	57
6. Sludge concentration in the upper part of the expanded layer, kg/m^3	9.8	9.6	9.3	9.7
7. Sludge concentration in the middle part of the expanded layer, kg/m^3	25.5	25.2	24.8	25.1
8. Sludge concentration in the lower part of the expanded layer, kg/m^3	42.2	41.4	40.2	41.2
9. Total biomass in the reactor, kg	3264	4662	5977	4644
10. Increase in biomass in the reactor before discharge, kg	–	1398	2717	1380
11. Coefficient of biomass growth, kg/kg_{COC}	–	0.08	0.076	0.079
12. Average ash content of activated sludge, %	–	29	31	30
13. Total active biomass in the reactor, kg	3264	3264	3260	3264
14. Total ashless substance of activated sludge, kg	–	2317	2249	2285
15. The equivalent of all BCO in COC(B), kg	–	3476	3374	3428
16. Load on activated sludge, $kg_{COC}/kg_{BCO}\cdot$day	–	0.504	0.52	0.51
17. The given rate of removal of organic matter in the reactor, $kg_{COC}/kg_{COC(B)}$	–	0.336	0.346	0.34

Table 3. Characteristics of sludge from the expanded layer.

Characteristics	Control period in 2018								
	September			October			November		
	1[a]	2[a]	3[a]	1	2	3	1	2	3
Sludge concentration, kg/m^3	41.4	25.2	9.6	40.2	24.8	9.3	41.2	25.1	9.7
Ash content of sludge, %	58	29	27	60	31	29	59	30	28
Sludge index (J), cm^3/g	18	30	78	19	31	81	18	31	77

[a] – Items 1,2,3 – the lower, middle and upper parts of the extended layer.

clearly defined elevations or depressions. The phase boundary (sludge-water) was traced at the same level, which indicates the levelling of the fluid velocity field and the same distribution of the nutrient substrate in the active sludge layer. The active sludge layer itself should obviously start from a height of 0.85-2.6 m, depending on the retention time of the biomass, counting from the time of discharge of excess sludge. Here, 0.85 m is the height to which sand particles can be hydrotransported, and 2.6 m is the level of compacted biomass (in 60 days) in the volume of 50-60 m^3 discharged from the reactor. During compaction of sludge, its concentration increases in proportion to the decrease in volume and reaches 80-100 kg/m^3 in the lower part of the reactor (depending on the time of compaction).

The specified height of the lighting zone (at least 1.0 m) does not need to be changed. Removal of biomass with a concentration (SS) of 81-83 g/m^3 during the control period ensures the necessary operation mode of the next stage of aerobic treatment and is within the recommended limits for anaerobic reactors [18].

Unloading (volumes) of fermented excess anaerobic sludge (without worsening the biodegradation of organic substances) should correspond to the volume of biomass growth in a compacted state (by 200 %): so when it is unloaded once a month – 25-28 m^3; when unloaded once every two months – 50-56 m^3. When the time between sludge discharges increases (2 months or more), its average mineralization (of discharged sludge) increases – from 62 to 70 % (according to analyses of sludge at sludge sites). One of the explanations for the mineralization of biomass can be an increase in the share of inert carriers – sand particles in the sludge mass, which are classified in the lower part of the reactor due to the greater mass of their particles with correspondingly smaller sizes. The discharged sludge needs further study, namely, the determination of the nature of active biomass carriers and the remaining active biomass in it.

According to the research results, the amount of ash (mineralization) of the crust floating on the water surface of the reactor is in the range of 52-55 %.

The obtained depth of decomposition (removal) of organic substances in psychrophilic anaerobic reactors with an upward flow of liquid was:

- for organic pollutants of various natures (SS and dissolved) (1167/2462)·100 % – 47.4 %, where 2462 kg/day – all average daily organic substances (SO and dissolved) at the entrance of the reactors during the observation period, 1167 kg/day – all organic substances removed from the reactors per day;
- for unloaded excess sludge – 40 %;
- for a pop-up crust – 35 %.

The study of the sludge index showed that the anaerobic sludge formed during the purification of household wastewater has a value of J = 18-81 cm^3/g. It settles quickly, especially the sludge of the lower and middle part of the expanded layer (J = 18-31 cm^3/g), which, with correct calculations of the upward liquid flow rates, will ensure hydraulic retention of the biomass in the reactor in the expanded layer. The analysis of the pH of wastewater and the pH of water in the reactors indicates a balanced passage of the process within the range of pH from 6.55 (deviations in previous periods) to 7.97 without loss of the oxidizing capacity of the facilities. That is, within the specified limits, in a psychrophilic anaerobic reactor with an upward flow of liquid, biomass inhibition did not occur and it remains active in the pH range of 6.55-7.97.

The maximum decrease in temperature (monthly average) was observed up to 14 ^{o}C (results of previous periods). However, this decrease does not affect the oxidizing power of the buildings. First of all, because changes in temperature (especially temperature) and pH of the liquid reactor did not occur instantaneously but increased (according to the control results), this probably allowed the attached microorganisms to adapt to environmental changes and not lose activity. As for the pH, the buffering of the volumes of the medium of the reactors (system) smooths out volley discharges of acidified effluents of the local dairy plant (non-regular status at this enterprise).

Extraction of both suspended solids trapped in sand pits and sand (aeration of sand pits) and their removal to anaerobic reactors will only improve the physical and sanitary-epidemic

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condition of the unloaded sand. It will dehydrate faster and be safer to release into the environment.

The re-fermented excess sludge discharged from the reactors (control period and previous ones) after 20-60 days (depending on the season) is already suitable for mechanized removal from the sites. Also, due to the rapid dehydration of sludge, its further decomposition and atmospheric air pollution do not occur (ash content does not increase). The dry sludge residue is a safe product and can be used in urban improvement, as an organic additive in land planning, etc. In traditional WWTP technologies, up to 30 cubic meters of excess sludge and sediments are removed from every 1,000 cubic meters of sewage effluent every day. For their dewatering, it is necessary to have at least 0.5 ha of sludge disposal sites (clause 6.388 [19]) in the case of the Kaniv – 2.0 ha. In our case, during unloading – 113 m^3 of sludge (humidity 92%) once every two months; the required area of the disposal sites is only 0.12 ha.

The specified characteristics that can be recommended for research and design organizations for process calculations or psychrophilic anaerobic reactors for domestic wastewater treatment with simultaneous treatment of raw sediments (perhaps also sludge) are summarized in table 4. It's important to note that these characteristics may need further clarification when dealing with anaerobic reactors and excess sludge from the aerobic purification stage.

Table 4. Summary table of obtained characteristics.

№	Parameters	Recommended value	Comparison[a]
1	The maximum speed of the upward flow, m/h	1.5	1.0
2	Maximum expansion of sludge volume, %	100	–
3	Sludge concentration in the reactor by SS, kg/m^3	25	25
4	Sludge concentration in the reactor for ashless sludge substance (ASS), kg/m^3	17.5	19
5	Volume load on the structure, kgCOD/m^3·day	0.94	1-4
6	Coefficient of biomass growth, kgASS/kgCOD	0.076	0.1-0.2
7	Sludge loading, kgCOD/kgASS·day	0.51	0.7-1.5[b] 0.1-0.3[c]
8	kgCOD/ kgCODB	0.2	0.3-0.7[b] 0.05-0.15[c]
9	Permissible limit of pH	6-8	5-8,5
10	Permissible wastewater temperatures, °C	≥14	≥15

[a] – characteristics are determined in the temperature range of 15-25 °C for industrial psychrophilic EGSB reactors;
[b] – for easily soluble organic substances;
[c] – for (SS) hardly soluble organic substances.

During the operation of sewage treatment plants using anaerobic fermentation at the first stage of wastewater treatment in a psychrophilic reactor, a significant amount of gas is released, which can be attributed to biogas by its origin. We have collected it in a sealed container and analyzed it. The results of the analysis are presented in table 5.

Table 5 shows that the obtained biogas contains, on average, about 75 % of organic gases – mainly methane, and about 25 % of organic ones – mainly carbon dioxide.

Based on the above research, we proposed a new municipal wastewater treatment technology "Biokonveier". The main advantage of our technology, in comparison with those introduced in the 20th century, is the guaranteed obtaining of standard indicators of purified wastewater: SS –

Table 5. Gas chromatographic analysis of biogas composition.

Gas	Sample 1, %	Sample 2, %
H_2	1.0	1.1
CO	0.2	0.3
CO_2	23.5	25.1
H_2S	0.01	0.01
Inorganic	**24.71**	**26.51**
CH_4	74.79	72.99
C_2	0.3	0.3
C_3	0.2	0.2
Organic	75.29	73.49

15 mg/dm^3; COD – 40 mg/dm^3; BCO_{20} –15 mg/dm^3; BCO_5 – 12 mg/dm^3; total nitrogen – 12mg/dm3; total phosphorus – 1.5 mg/dm^3.

In the case of increased requirements for discharge into a reservoir with a slight dilution of wastewater, further treatment of wastewater using sand self-washing filters or filters with liquid microfiltration is provided: SS – 10 mg/dm^3; COD – 28 mg/dm^3; BCO_{20} – 10 mg/dm^3; BCO_5 – 8 mg/dm^3; total nitrogen – 12 mg/dm^3; total phosphorus – 1.5 mg/dm^3.

Biological treatment facilities "Biokonveier" consist of:

- a special anaerobic section – from an anaerobic psychrophilic reactor with an expanded layer of sludge, where the anaerobic stage of sewage treatment, destruction of raw sediment and preparation of the nutrient substrate for the next stages of purification, selection of phosphorus-accumulating microorganisms, removal of retained phosphorus with excess sludge takes place;
- a special section where aerobic and anoxic processes periodically take place – ARS- aeration tank, which works with a change of aerobic and anoxic regimes and where the stages of destruction of carbon compounds, nitrification and denitrification of nitrogen, removal of orthophosphates from the solution take place;
- aerobic section (post aeration tank), where the stages of oxygen saturation of the mixture of wastewater and activated aerobic sludge take place, final oxidation of possible residues of wastewater pollution, removal of molecular nitrogen into the atmosphere, removal of excess sludge from the technological process;
- settling tank, where wastewater and activated sludge are separated in anoxic conditions, sludge compaction is required, compacted sludge is diverted to the ARS aeration tank (60-100% recirculation);
- adagulation anoxic compactor of surplus sludge of anaerobic and aerobic stages of sewage treatment, where contact coagulation (compaction) of sludge is carried out in anoxic conditions to exclude nitrates from entering the anaerobic reactor (at the head of the structure) with sludge water;
- equipment for the preparation and dosing of dephosphatization reagents, in the case of cleaning a mixture of domestic and industrial wastewater, for example – effluents from dairies, which have an increased content of phosphorus compounds.

"Biokonveier" facilities for the carbon, nitrogen and phosphorus compounds removal are schematically shown in figure 1 and figure 2. Figure 1 shows the ARS-aeration tank of periodic action, which works under aeration conditions – carbon oxidation and nitrification of ammonium nitrogen, removal of orthophosphates, and figure 2 – in conditions of denitrification, removal of carbon compounds when aeration of the ARS-aeration tank is turned off.

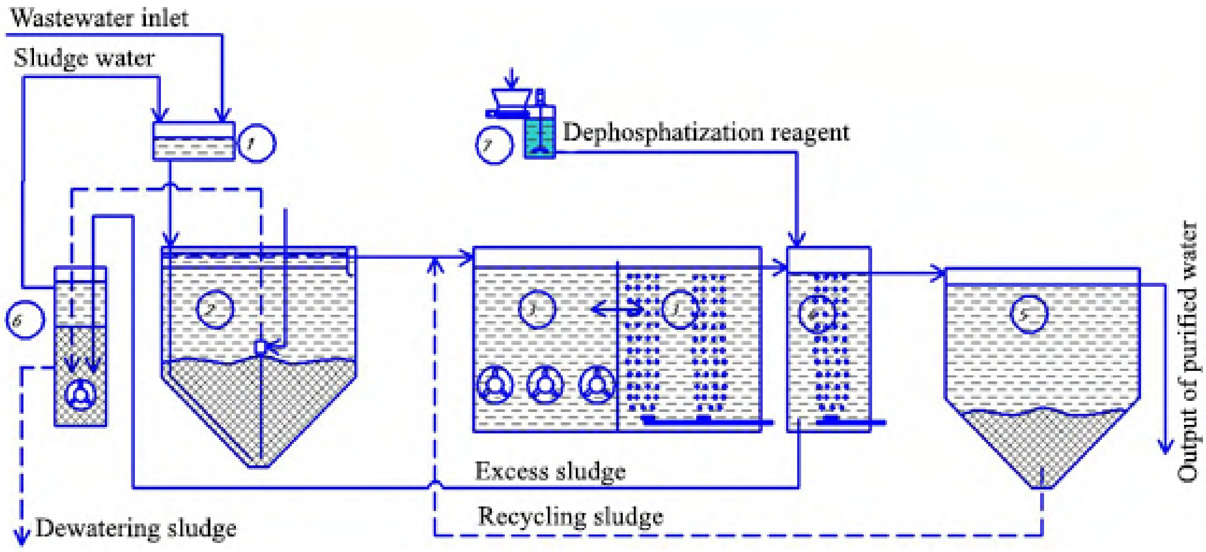


Figure 1. Block diagram of excess carbon, nitrogen and phosphorus from municipal or equivalent effluents removal: 1 – receiving capacity; 2 – anaerobic psychrophilic reactor; 3 – ARS – aeration tank periodic inspection; 4 – post-aeration tank; 5 – settling tank; 6 – adagulation anoxic sludge sealer; 7 – dephosphatization equipment. Conditions for a mixture of wastewater treatment and sludge: anaerobic – the first stage of wastewater treatment; aerobic – the second stage of wastewater treatment; aerobic – the third stage of wastewater treatment.

Facilities for biological treatment of sewage from carbon, nitrogen and phosphorus compounds (figure 1, figure 2) have receiving capacity (1), anaerobic psychrophilic reactor with an expanded layer of sludge (2), ARS-aeration tank periodic inspection (3), post aeration tank (4), settling tank (5), adagulation anoxic sludge sealer (6), equipment for introducing dephosphatization reagents (7).

The anaerobic psychrophilic reactor in the lower part has a distribution system for the supply of sewage, a pipeline for the removal of excess sludge, and, if necessary, can be equipped with a cap for collecting biogas. Treated effluents under anaerobic conditions together with removed anaerobic sludge (no more than 85-100 mg/dm^3) are constantly diverted from the upper part of the reactor to the ARS-aeration tank. In the last one, an aeration system is installed, which is protected from water ingress when the air is turned off, and flow generators ensure the movement of a mixture of sludge and wastewater to prevent the fall of suspended particles (sludge) when the air is turned off, when the section is switched to the denitrification mode, to ensure high-quality mixing of effluents coming from the anaerobic reactor with the liquid of the pool, for internal recirculation of the mixture (up to 100%). From the upper part of the ARS-aeration tank, liquid in calculated volumes constantly flows into the post-aeration tank. The last one is also equipped with a protected aeration system and reagents for dephosphatization, including ferrous iron, which needs oxidation, and can be fed into its capacity as needed. From the lower part of this section, excess sludge is also constantly diverted for compaction, from the upper part – treated sewage with sludge for separation in the settling tank. If necessary, a polymer nozzle can be loaded into the upper part of the sump to improve water purification. The settling tank is also equipped with a system for the permanent removal of compacted activated sludge of the required concentration. Surplus sludge from the post-aeration tank is sent to the

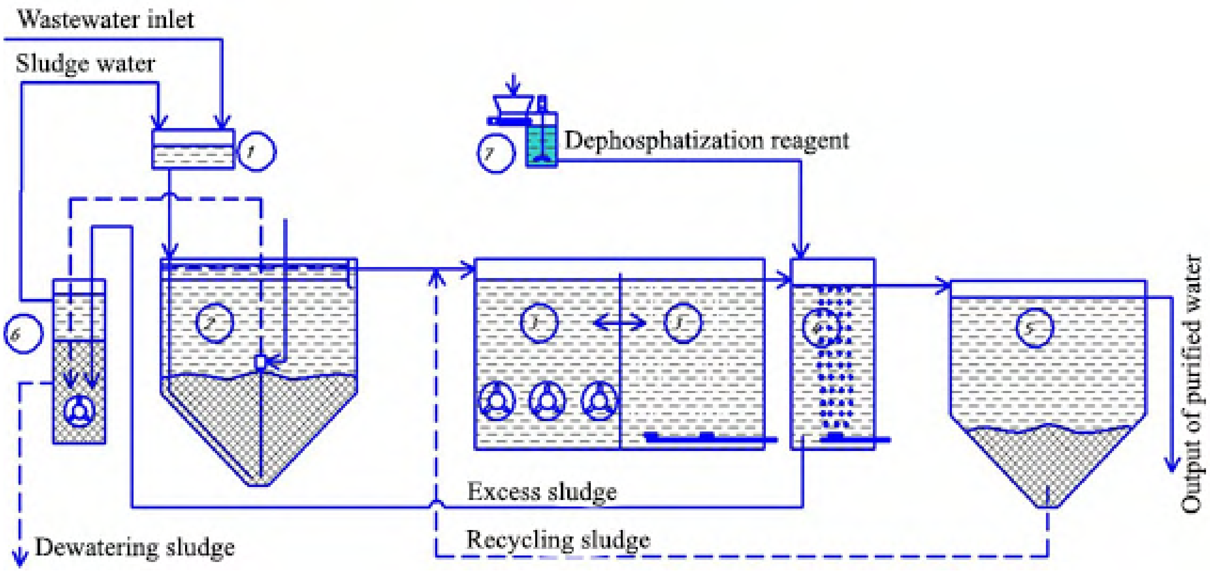


Figure 2. Block diagram of excess carbon, nitrogen and phosphorus from municipal or equivalent effluents removal: 1 – receiving capacity; 2 – anaerobic psychrophilic reactor; 3 – ARS – aeration tank periodic inspection; 4 – post-aeration tank; 5 – settling tank; 6 – adagulation anoxic sludge sealer; 7 – dephosphatization equipment. Conditions for a mixture of wastewater treatment and sludge: anaerobic – the first stage of wastewater treatment; anoxic – the second stage of wastewater treatment; aerobic – the third stage of wastewater treatment.

lower part of the adagulation anoxic sealer, where it is periodically mechanically mixed with the well-structured sludge of the anaerobic reactor (the flakes are compact, integral, there are granular forms) the particles of which have much larger linear dimensions. As a result of contact coagulation, silt particles thicken (compaction). After settling and separating the mixture, the sludge water is pumped into the receiving tank of the anaerobic reactor, and the compacted sludge is sent for dewatering [20].

The feature of the “Biokonveier” station is receiving purified wastewater and safe waste. In addition, the minimal amount of discharged sediments puts our proposed biotechnology in an exceptional position compared to existing facilities for domestic sewage or similar effluent treatment. The development of the “Biokonveier” station with a capacity of 1.0 to 15.0 thousand m^3/day with the use of sediments and sludge active processing is an example of the introduction of biotechnologies with modern hardware implementation.

The “Biokonveier” station is made of a single closed block (figure 3). In the underground part, sewage treatment removed biomass and excess microorganism’s destruction, which purified water, takes place. Various technological equipment, control and management systems, administrative and household and warehouse premises are located in the above-ground part. Emission gases released from process tanks are cleaned and disinfected before being released into the atmosphere. Air conditioning is provided in administrative and domestic premises, and ventilation is necessary in production areas to create a safe atmosphere.

The output of biogas ($CH_4 + CO_2$) produced in anaerobic fermentation is determined by COD removal in an anaerobic reactor, as well as chromatographically:

$$1\text{kg COD} \rightarrow 0.35\ \text{m}^3\ \text{CH}_4 + 0.188\ \text{m}^3\ \text{CO}_2,$$

where the CH_4 content in the gas mixture is 65-70%.

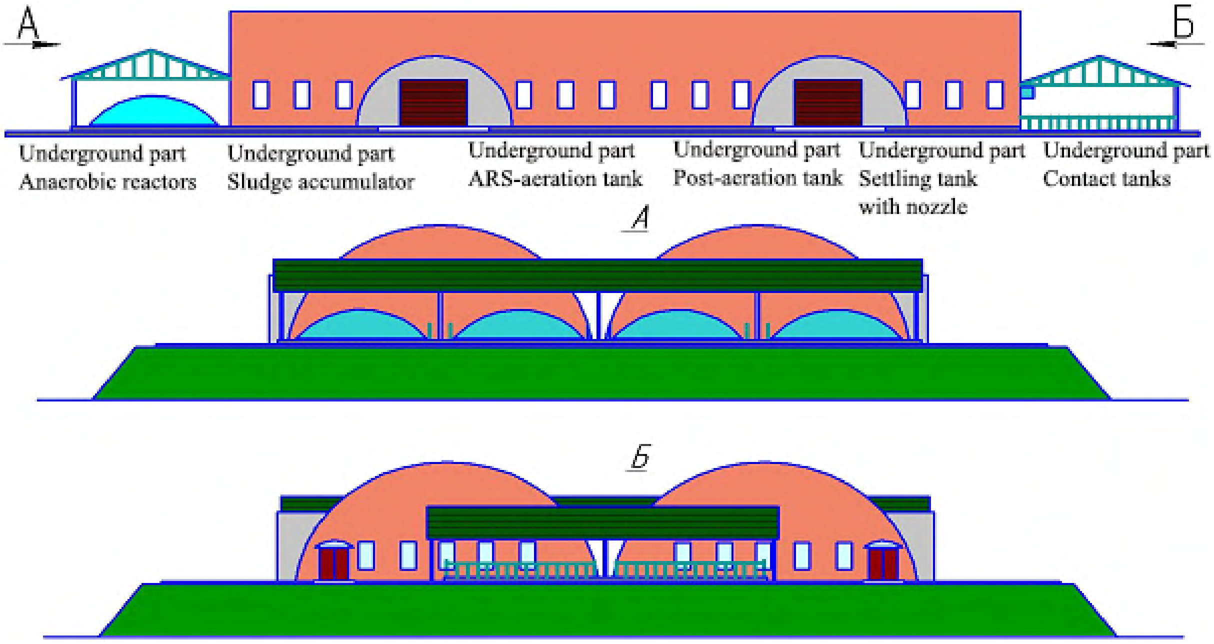


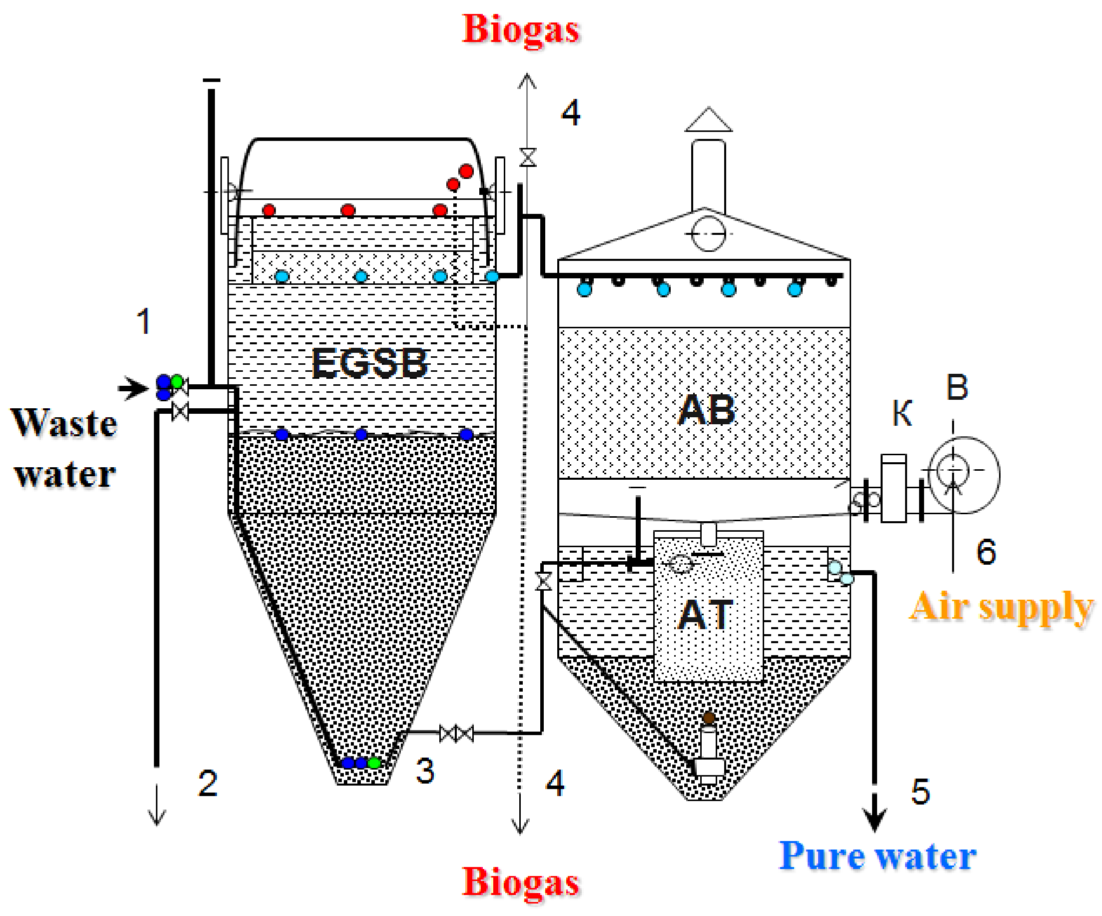
Figure 3. Industrial design of the "Biokonveier" station with a 10,000 m^3/day capacity.

As a result of the use of energy-saving equipment, modern aeration systems, effective management of technological processes in real-time modes, and the use of biogas, electricity consumption at the "Biokonveier" stations will be only 0.2 to 0.4 kWh per m^3 of treated wastewater [20].

The proposed model-concept was successfully used during the design works for the reconstruction of the Kaniv WWTP. Two EGSB psychrophilic reactors, which were converted from existing two-tier sedimentation tanks, were put into operation. This new technology only required 0.5 ha of land for depositing the sediments produced, while the traditional method required 2.0 ha of sludge sites. However, the practical results from several years of operating the sludge sites showed that only 0.12 ha were used. Furthermore, a one-time dose of discharge of excess sludge from the reactors was determined to be 50 m^3 per half month. It is important to note that the significant rate of dehydration of sediments during the process did not result in their decomposition, which could have caused environmental pollution. The sediments were further cleaned in aerobic conditions using reconstructed aerofilters and secondary sedimentation tanks that were converted into aero-settling tanks with jet aeration.

The long-term operation of the anaerobic reactor, created based on the primary sedimentation tank, and the obtained positive results of wastewater treatment confirm the perspective of using the selected approach in the technological schemes of urban sewage treatment.

The analysis of the experimental results obtained in the field led to the unequivocal conclusion that the implementation of the developed approach, where the first stage is the anaerobic treatment of wastewater in psychrophilic conditions, provides, first of all, a significant (by 4-5 times) reduction in the dry matter of sludge with good water-releasing properties, high ash content and stability, which means a reduction in the area of sludge sites. This, in turn, ensures the unloading and improvement of the operation of the aeration tank with insignificant capital costs for the reconstruction of the existing Kaniv WWTP and their modernization with an increase in the capacity of the facilities. An important positive is that conversion of existing WWTP facilities (primary clarifiers, two-tier clarifiers, etc.) into EGSB reactors is possible by the organizations that operate these facilities. In addition, the complex of conducted research and accumulated operational experience created the necessary prerequisites for the development of low-cost WWTP projects for new construction with specific electricity consumption of no more than 0.2-0.5 kWh/m^3 of treated sewage, with the possibility of manufacturing in factory conditions relatively cheap compact cleaning plants. The system's resistance to various hydraulic and organic regimes, and, therefore, the absence of sewage averaging facilities, makes the technological scheme of anaerobic-aerobic treatment even more compact with a reduction in the area under treatment facilities, which is especially important for enterprises with individual treatment facilities. Combining in the main technological line the biological processes of low-temperature anaerobic decomposition and aerobic oxidation of the organic component of sewage, deep processing of sediment and excess sludge under anaerobic conditions in the EGSB-reactor, as well as the use of biofilters combined with aeration tank-settlers, which are practically equivalent components of aerobic part, makes it possible to fully decentralize sewage treatment with the prospect of complete automation and remote control of the treatment process. Inclusion in the technological scheme of the biogas production process will allow the WWTP to provide



● - Waste water; ● - Anaerobic purified water; ● - Biogas (CH_4, CO_2); ● - Aerobically purified water; ○ - Air aeration; ○ - Pure water; ● - Excess sludge.

Figure 4. Complete scheme of combined facilities for biological wastewater treatment: EGSB – anaerobic EGSB reactor; AB – anaerobic biofilter; AT – aeration tank-settler; B – fan; K – air heater; 1 – supply of sewage for treatment; 2 – removal of excess sludge; 3 – recirculation line; 4 – biogas outlet; 5 – purified water outlet; 6 – air supply.

its own heat needs (heating, hot water supply, etc.).

Figure 4 shows a complete scheme of combined facilities for biological wastewater treatment and processing of raw sediments and sludge.

Nowadays, only the anaerobic part of the water purification process works successfully, effectively fulfilling its function. The clarified water is then purified on artificial bioplates to meet the existing standards for discharge into the Dnipro River.

4. Conclusion

The process of biodegradation of organic impurities in reactors, the actual loading of flow-through psychrophilic reactors in terms of organic substances, the amount of biomass growth, and the biomass biodegradation rate were studied. The output of biogas obtained in a psychrophilic flow reactor and its composition were determined. A model-concept of treatment facilities has been developed. The technology of municipal sewage deep cleaning from biogenic elements "Biokonveier" is proposed. Anaerobic treatment of wastewater in psychrophilic conditions provides a 4-5-fold reduction in dry matter of sludge with good water-releasing properties, a reduction in the area of sludge sites by an order of magnitude and allows for the creation of inexpensive projects of municipal sewage treatment plants for new construction with a specific electricity consumption of no more than 0, 2-0.5 kWh/m^3 of treated sewage. Systematic studies of the process of anaerobic wastewater treatment at Kaneva sewage treatment facilities allow for the development of recommendations and calculation methods for the design of anaerobic psychrophilic flow reactors for the treatment of municipal sewage effluents or a mixture of municipal and industrial effluents with a BOD of up to 2.0 g/dm^3. At the same time, use them as combined structures for partial destruction of the organic component of sewage and mineralization of sediment and excess sludge from the aerobic treatment stage, obtaining biogas to meet the energy needs of the treatment plant site. Also, justify the expediency of replacing in cities and villages of Ukraine anaerobic psychrophilic flow reactors of primary settling tanks in sewage discharge treatment schemes.

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Application of fine waste from iron ore beneficiation in reinforced concrete structures with basalt-plastic reinforcement

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Abstract. One of the main development programs of each country is the control and utilization of industrial waste since the sustainable development of this industry is accompanied by the greatest environmental pollution. Iron ore beneficiation byproducts are artificial quartz-iron mineral mixtures that are fed into sludge ponds that form the so-called tailings ponds in the form of pulp. Tailings ponds occupy more and more territory every year and have a significant negative impact on the environment. At the same time, industrial waste from iron ore enrichment, the so-called tailings, is used as a fine aggregate in concrete mixtures to replace quartz and construction sand. Studies show that a 40% replacement of quartz sand with fine iron ore dressing waste is optimal for the manufacture of concrete mixtures without any adverse effect on strength and durability properties. The paper considers the stress-strain state of beams in the second group of limit states made of concrete mixtures at 100% replacement of quartz sand with fine plant protection products waste. The percentage of reinforcement of beam sections of all series and the class of concrete were assumed to be the same for samples of all series. The results of experimental tests showed almost comparable results of crack resistance of beams reinforced with metal reinforcement and with hybrid reinforcement. At a load of 70% of the destructive capacity, BM and BMD beams do not exceed the maximum permissible width of normal crack opening, and BMBD beams do not exceed the maximum permissible width of 60%.

1. Introduction

One of the strategic sectors of Ukraine's economy is the mining and metals sector, whose sustainable development provides the largest tax payments to the budget, stimulates the growth of other sectors of Ukraine's economy, and provides more than 200,000 jobs [1]. At the same time, the development of this industry is accompanied by the largest environmental pollution, as by-products are an integral part of each production stage.

Iron ore enrichment by-products are overburden and host rocks from ore mining and by-products of their enrichment. The beneficiation by-product makes up 40-60% of the beneficiation material and is a non-cohesive material consisting of sharp-angled rough grains – an artificial quartz-iron mineral mixture that is less homogeneous than quartz sand in terms of both particle size distribution and chemical composition. Waste from iron ore beneficiation in the form of pulp is removed through pipelines to sludge ponds, which form the so-called tailings ponds.

Today, there are about 465 tailing dumps in Ukraine, which contain more than 6 billion tons of waste from various industries and, occupying large areas (over 7,600 hectares in Kryvyi Rih alone [1]), have a significant negative impact on the environment:

- flooding of adjacent territories;
- groundwater pollution;
- acting as a powerful source of dust generation due to the drying of the upper part of the beaches.

At the same time, according to the State Statistics Service of Ukraine, the volume of iron ore enrichment is not sustainable and increases every year (figure 1), which leads to an even greater accumulation of industrial waste in tailings ponds.

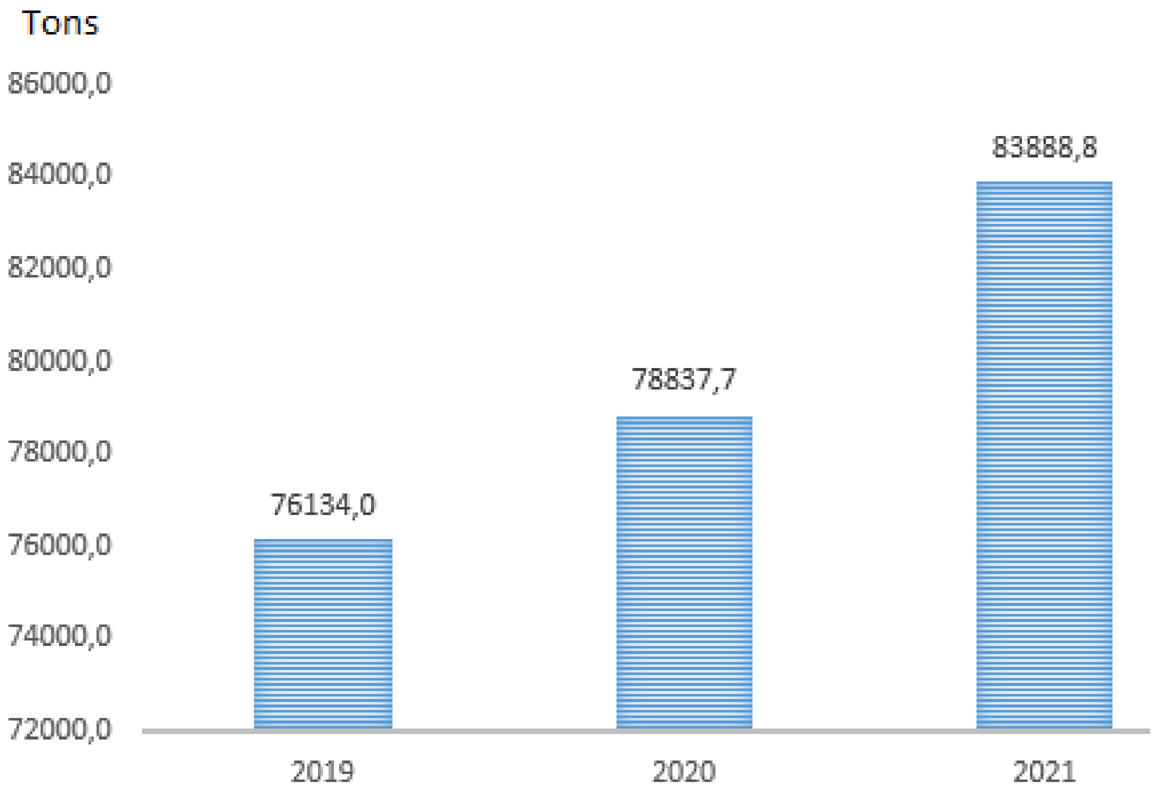

Figure 1. Production of non-agglomerated iron ore and concentrate (gross production).

At the same time, industrial waste from iron ore beneficiation, the so-called tailings, is used as a secondary raw material for the production of construction materials:

- in construction mortars, as fine aggregates in heavy and extra heavy concrete;
- for the construction of artificial foundations for roads, buildings, structures, backfills, etc.

However, there is no publicly available static data on the volume of plant protection products waste utilization or their use in the construction industry.

In the production of concrete mixtures, it is plant protection products waste that is a full-fledged alternative to quartz sand, which is a versatile natural material used in various industries: glass, chemical (including for filtration), construction (concrete mixtures, plaster, etc.) and metallurgy (molding sands for metal casting).

Quartz frac sand is extracted by open pit mining or by dredging from natural deposits in floodplains of rivers and lakes. Deposits of construction sand are located almost all over Ukraine, but river sand is the most popular on the market as it contains a minimum amount of pollutants.

According to open sources of information on construction sand production in the country:

- about 650 deposits are officially registered and only 230 are officially under development. However, according to indirect unofficial sources, the total number of construction sand deposits is up to 900;
- in 2017-2020, the production of construction sand amounted to 13.7-15.5 million tons per year, according to the data provided on the state website "Data Portal of the Extractive Industry of Ukraine". At the same time, according to indirect unofficial sources, the total annual production reaches up to 25-35 million tons per year;
- construction sand production, according to the State Statistics Service of Ukraine [2], almost doubled in 2021 compared to 2014 (figure 2) and amounted to 19.2 million tons.

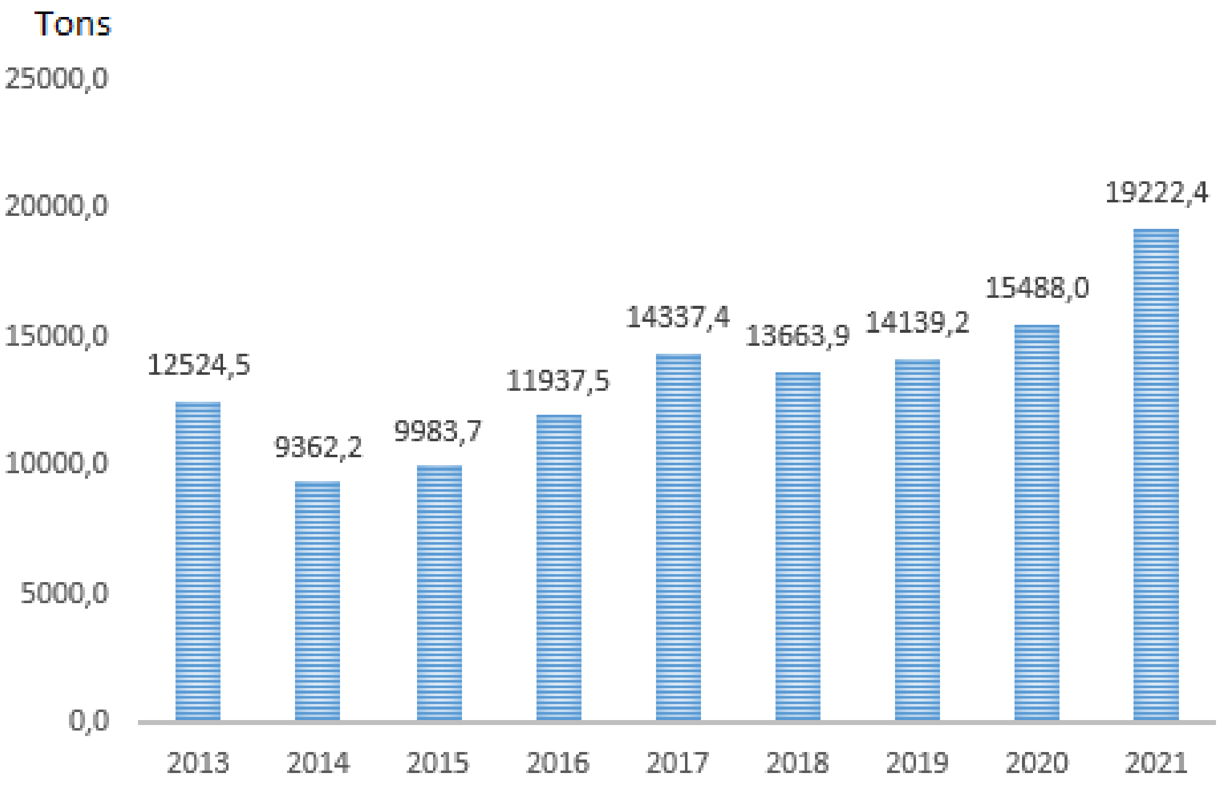

Figure 2. Construction sands, such as clay, kaolin, feldspar (except for flint and metal-bearing sands) (gross production).

It should be noted that the extraction of construction sand from natural deposits in the floodplains of rivers and lakes leads to:

- changes in the bottom landscape, which forms the so-called stagnant zones where aquatic life lacks oxygen and water quality is significantly reduced;
- soil erosion and salinization of aquifers.

Moreover, in a new report of the United Nations Environment Program of 2022 [3], it is proposed to recognize sand as a strategic resource at the international level due to the fact that its volumes are rapidly decreasing and its extraction is accompanied by negative environmental impact.

In view of this, the wider use of small waste of plant protection products, pulp, instead of construction sand, for the manufacture of reinforced concrete structures, on the one hand, will reduce the amount of iron ore beneficiation waste entering tailings, and on the other hand, will reduce the demand for construction sand. This will also reduce the cost of manufacturing such structures.

In recent years, fiber-reinforced polymers (FRP) have been increasingly used in the manufacture of reinforced concrete structures to reduce costs and take certain advantages. This is due to certain advantages of composite reinforcement (FRP) over metal reinforcement: higher tensile strength, high resistance to aggressive environments (does not corrode), low thermal conductivity, dielectricity, non-magnetism, and relatively low weight. At the same time, composite reinforcement has not only advantages but also disadvantages, the main one being a lower elastic modulus compared to metal reinforcement, which negatively affects the rigidity of structures [4].

Within the country, carbon fiber-reinforced polymers (CFRP) and aramid-fiber-reinforced polymers (ARFP) are of limited use due to their high cost, while basalt fiber-reinforced polymer (BFRP) and glass fiber-reinforced polymer (GFRP) are comparable in price and in some cases lower than metal reinforcement. Further research into the performance of BFRP and GFRP in reinforced concrete structures led to the development and publication in 2012 of relevant regulations for the design and manufacture of structures using this composite reinforcement. However, the use of basalt fiber reinforcement polymer (BFRP) is more promising than glass fiber reinforced polymer (GFRP) due to better mechanical and operational properties (elastic modulus, deformability, resistance to alkaline environment) [5, 6].

2. Literature review

Experimental studies of the possibility of using small plant protection products waste from slurry pits as fine aggregate in the production of concrete mixtures date back to the 1960s. In 1982, a collection of works was published, which analyzed and summarized the results of the physical and mechanical performance of both concrete mixtures and reinforced concrete structures made with fine aggregates from plant protection products waste, and compared them with traditional concrete on quartz sand [7]:

(i) comparison of concrete mixtures:

- concrete composition can be determined by well-known methods;
- the strength of the concrete mixture is 11.8% higher;
- stiffness and water resistance of the concrete mixture are higher;
- equal corrosion resistance;
- reduced mobility, which is solved by the use of appropriate plasticizers.

(ii) comparison of reinforced concrete structures:

- the load-bearing capacity of off-center compression racks under short-term load is 20-25% higher;
- the experimental values of beam deflections are lower by 24.6%;
- the same deflection in the slabs was recorded under the action of a bending moment, which was 28.3% higher than in the slabs of the same series made of concrete on quartz sand. The performance of slabs made of concrete with plant protection products waste exceeds the calculated values: strength – by 20-28%; stiffness – by 40-45%, deformability is lower by 37-40% and 33-34%.

However, it was only in the 1990s, with the publication of the relevant regulations, that the widespread use of fine plant protection products waste as fine aggregate in concrete mixtures became possible in construction. At the same time, the results of further studies of concrete mixtures indicate certain reservations about the complete replacement of quartz sand with small waste plant protection products in concrete mixtures.

Thus, in work [8], the physical and chemical properties of concrete were investigated both in the form of a mixture and at different times after hardening. For the study, concrete mixtures were made with partial replacement of quartz sand with small waste of plant protection products – 10%, 20%, 30%, 40%, and 50%. General studies have shown that, depending on the physical and chemical composition of small waste plant protection products, the replacement of up to 40% is optimal for the manufacture of concrete mixtures without any harmful effects on the strength and durability properties. At a replacement rate of 50% or more, it is recommended to add plasticizers due to a decrease in concrete strength.

In the work [9], similar studies were conducted and similar test results were obtained – the replacement of 40% of quartz sand with fine plant protection products in concrete mixtures gives the maximum compressive strength compared to a mixture of quartz sand or in mixtures in which plant protection products are introduced in other proportions.

Experimental studies were conducted for M20 concrete with the replacement of sand by 10%, 20%, 30%, 40%, 60%, 80% and 100% of small waste plant protection products [10]. The maximum increase in compressive strength was obtained at 40% sand replacement. Also, it was found that the strength of reinforced concrete beams working in bending is also maximum at 40% sand replacement.

And the results presented in the work [11] showed somewhat different results of testing concrete mixtures with 100% replacement of quartz sand with fine plant protection products waste. The strength of concrete cubes of the T100 series made using the small waste of plant protection products, is 3.3% higher than the control series of T0 cubes made of quartz sand.

This difference in the results obtained by scientists from different countries is explained by the unstable and heterogeneous composition of fine iron ore waste due to the specifics of the technological processes of iron ore beneficiation at individual enterprises, as well as the regular modernization of their equipment. Therefore, the tailing dumps of each enterprise require separate studies to clarify the chemical and physical and mechanical properties of the tailings for the possibility of their further widespread use in the construction industry.

The results of experimental studies conducted by various scientists indicate that there are no restrictions on the use of BFRP reinforcement in reinforced concrete structures working in bending, made of concrete mixtures on quartz, construction, and sand [5, 6, 12, 13]. As for the structures reinforced with BFRP made of concrete mixtures containing small waste of plant protection products, such information is either absent or very limited.

The lack of experimental studies of the performance of bending structures reinforced with basalt plastic reinforcement made of concrete with fine aggregate of plant protection products hinders the updating of regulatory documents and the increase in demand for concrete made from fine plant protection products instead of quartz sand.

In this regard, the company has previously:

- developed a program for experimental testing of beams;
- prototypes of beams were manufactured;
- experimental tests of the beams were conducted;
- analysis of the stress-strain state of the prototypes of the beams according to the first group of the limit state [14].

Below are the crack resistance values of the test specimens of beams reinforced with both metal and basalt-plastic reinforcement. The comparison of indicators was carried out according to the criterion of different compositions of the concrete mixture of the beam samples: concrete on quartz sand and concrete with complete replacement of quartz sand with plant protection products waste.

3. Results

The experimental test program provided for the manufacture of 6 series of prototypes of concrete reinforced beams, three beams in each series table 1.

Table 1. Experimental test program.

Beam series	Reinforcement of the tensile zone	Reinforcement mark
BM	2ø12	Metal
BMD	2ø12	Metal
BB	2ø12	BFRP
BBD	2ø12	BFRP
BMB	2ø8,2ø8	Metal, BFRP
BMBD	2ø8,2ø8	Metal, BFRP

In accordance with the current requirements, the prototypes of all series were reinforced. The scheme of reinforcement of beam samples is shown in [14]. The reinforcement of the specimens was intended to achieve the destruction of the beams of the control series due to the destruction of the stretched reinforcement. To allow for a correct comparison of test results, the percentage of reinforcement of beam sections of all series and the concrete class were assumed to be the same for specimens of all series. The BM series, made of concrete on quartz sand, was taken as the control series of beams.

For the reinforcement of the specimens, metal (A400) and basalt-plastic (BFRP) reinforcement provided by the manufacturer of composite reinforcement, Technobasalt-Invest LLC, Ukraine, was used. The mechanical characteristics of the reinforcement are shown in [14].

For concreting, concrete of class C25/30 was used, which was produced at a concrete-mixing plant. Beams of the BM, BB, and BMB series were made of concrete mix with quartz sand as a fine aggregate, and beams of the BMD, BBD, and BMBD series were made of concrete with 100% replacement of quartz sand with small plant protection products waste. The latter is a fractionated quartz-iron mineral mixture with a density of 1,500-1,600 kg/m^3. The composition of concrete mixtures is shown in table 2.

Table 2. Composition of concrete mixes per 1 m^3.

Composition	Units of measurement	On industrial waste	On river sand
Cement	kg	380	380
Pulp	kg	750	0
Sand	kg	0	720
Gravel	kg	1200	1200
Water	1	180	180
Additives (Relaxon)	1	20	20

Short-term tests of the beams were carried out on a hydraulic press P-125 according to the scheme of a single-span free-lying beam. The diagram of the stand and the stand itself for testing experimental samples of beams in bending are shown in [14].

In the process of crack development in the tensile zones of concrete, three stages are distinguished: the appearance of cracks when they are still invisible; the appearance of cracks when they become visible with a microscope; and the opening of cracks to the maximum possible values. For elements with a normal reinforcement content, the last two stages are mainly considered: crack initiation and crack opening.

Based on the results of the experimental tests of the beams, table 3 shows the information on the cracking forces of the beams.

Table 3. Experimental cracking forces of the beams.

Beam series	Average destructive load, kN	Force determ., mm	Force of cracking, kN
BM	70.22*	50.0	39.24
BMD	75.87*	50.0	34.30
BB	100.88	70.0	14.22
BBD	96.06	70.0	17.33
BMB	96.06 (45.13*)	70.0	26.16
BMBD	99.24 (49.70*)	70.0	32.70

* Specified force corresponding to the beginning of yielding of metal reinforcement.

The results obtained, summarized in table 3, indicate that the moment of cracking in the beams of the BBD and BMBD series occurred at a load that was 21.9% and 25.0% higher than that of the BB and BMB series, respectively, and in the BMD series beams – 12.6% lower than that of the BM series. The moment of cracking for beams of the BB and BBD series occurred at more than half the load compared to the control series of BM beams.

The figures (figure 3, figure 4, figure 5) shows the graphs of the "load – crack opening width" dependence separately for the series with the same reinforcement.

The tendency to increase the width of the normal crack opening of beams under load made of concrete on fine plant protection products waste shows almost comparable results with the series of beams made of concrete on quartz sand. The overall performance of the beams of all series under load showed a direct dependence on the type of reinforcement used in the tensile zone.

Beams reinforced with metal, BM, and BMD series, showed typical performance as for beams with traditional reinforcement. The first normal cracks appeared in the pure bending zone at a load of 0.3-0.4 of the destructive load. Further increase of the load led to the appearance of new normal cracks and an increase of their width. Thus, for the BM and BMD beam series, the width of the crack opening at 5.0 t and 7.0 t is the same, and in other cases the difference ranges from -20.0% to 23.5%. The beginning of reinforcement yield was recorded at a load of 0.9 of the destructive load, which caused the destruction of the beams with the compression of the concrete of the compressed zone.

The beams with basalt-plastic reinforcement of the BB and BBD series showed the largest values of the width of normal cracks, which is explained by the lower elastic modulus of the BFRP reinforcement itself. At a level of 0.1-0.2 of the destructive load, the first normal cracks appeared, and at the destructive load of 0.5-0.6, inclined cracks began to appear. A uniform location of cracks was noted, with a step of 100-150 mm, along the length of the beam. Figure 4 shows an almost linear dependence of the increase in the values of the width of normal cracks with increasing load, which is typical for beams with composite reinforcement due to the lack of yield properties of the latter. The crack opening widths of the BBD series beams showed larger values compared to the BB series beams at all stages of loading, and the difference ranged from

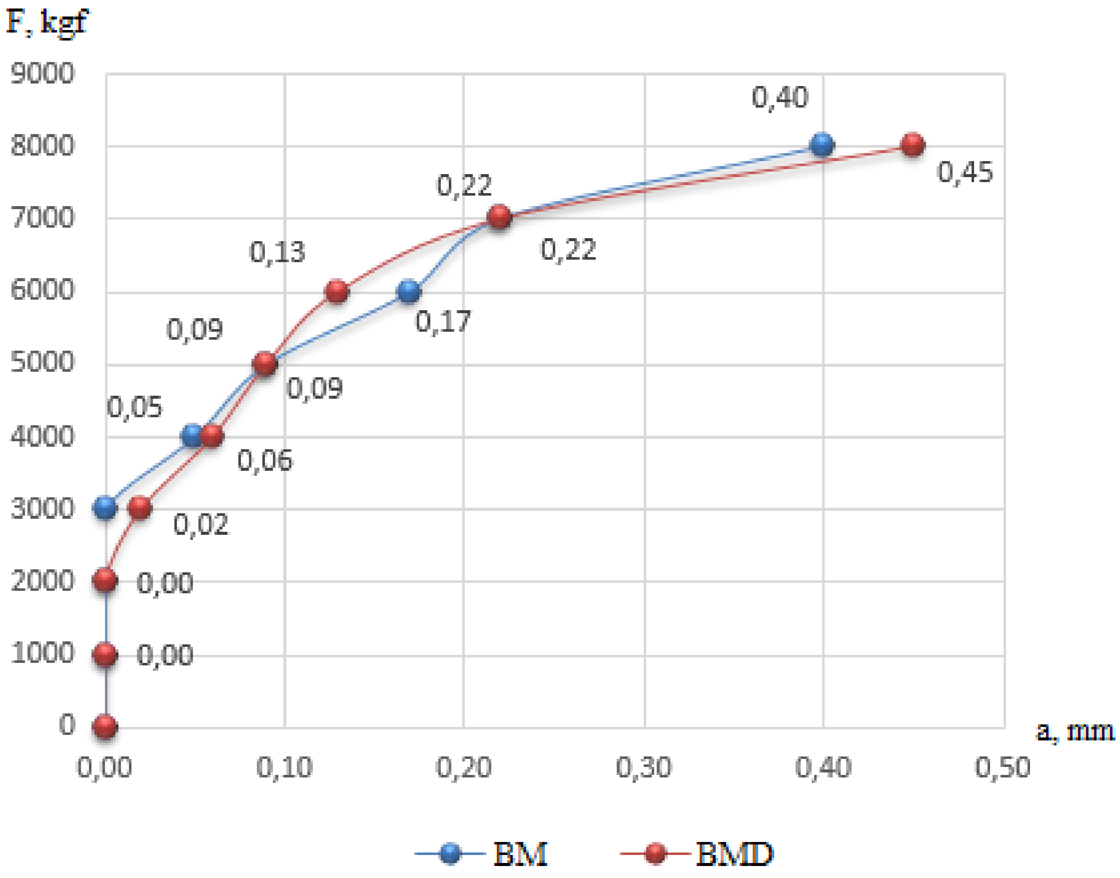

Figure 3. Graph of dependence F – a of BM and BMD beams.

-47.1% to -11.5%. The destruction of the beams occurred due to the crushing of the concrete of the compressed zone. No rupture or slippage of the BFRP reinforcement rods was observed.

The development of normal cracks in beams with hybrid, metal, and basalt-plastic reinforcement, of the BMB and BMBD series can be divided into two stages – before and after the onset of metal reinforcement yielding. At a level of 0.2-0.3 of the destructive load, the first normal cracks began to appear. Up to a level of 0.4...0.5 of the destructive load, the performance of the beams was similar to the BM and BMD series beams, which is explained by the predominant influence of metal reinforcement. After the appearance of reinforcement fluidity, basalt-plastic reinforcement begins to exert the main resistance to load. The behavior of the beams becomes similar to that of the BB and BBD series – the number and width of cracks increases. The destruction of the beams occurred due to the compression of the concrete of the compressed zone with the simultaneous complete or partial rupture of the BFRP reinforcement fibers. It should be noted that in the case of a series of BMBD beams made of concrete on fine plant protection products waste, the crack opening width was smaller at all stages of loading compared to a series of BMB beams.

For further analysis of the obtained values of the widths of the normal crack opening of the experimental beams and the limit values according to current standards, table 4 was compiled.

Since the test specimens of beams of all series do not contain tension reinforcement, reinforced concrete beams must meet the category of requirements for crack resistance 3c, which is limited only by the limit value of the calculated crack opening width of 0.3 mm in accordance with clause

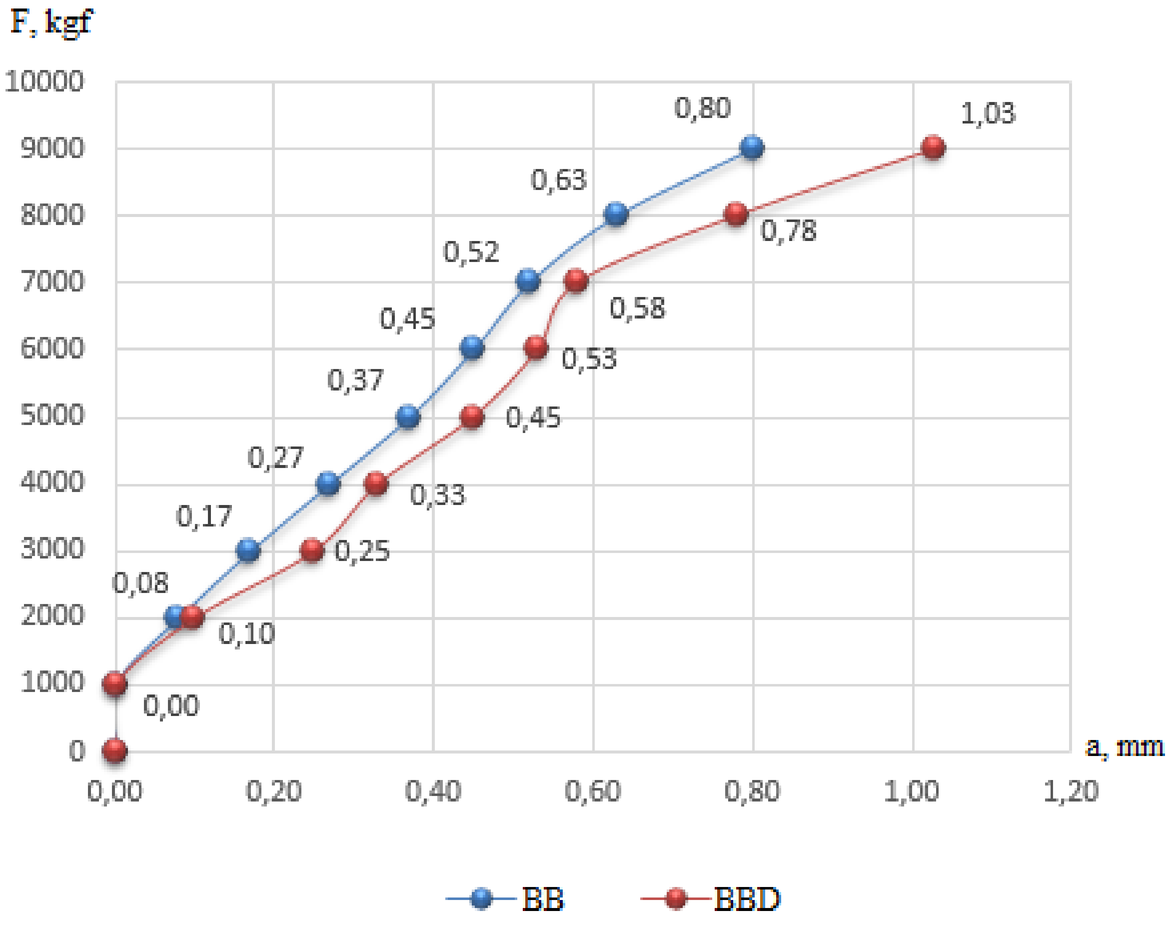

Figure 4. Graph of dependence F – a of BB and BBD beams.

Table 4. Average experimental values of the width of opening of normal cracks in the test beams.

Beam series	Force determ., kH	Average crack width, mm	Permissible value, mm
BM	50.0	0.09	0.3
BMD	50.0	0.09	0.3
BB	70.0	0.52	0.3
BBD	70.0	0.58	0.3
BMB	70.0	0.38	0.3
BMBD	70.0	0.35	0.3

3.95 [15]. Less stringent requirements for the maximum crack opening width are imposed when using basalt-plastic reinforcement in structures, which is explained by the material's resistance to aggressive environments. Thus, according to table G.4 [16], basalt-plastic reinforcement belongs to Group IV, in which the crack opening width due to corrosion conditions in accordance with Annex D [16] is not standardized. According to clause 5.2.4 of the norms [17], the maximum width of crack opening in concrete elements with basalt-plastic reinforcement should be determined taking into account aesthetic and psychological requirements and should not

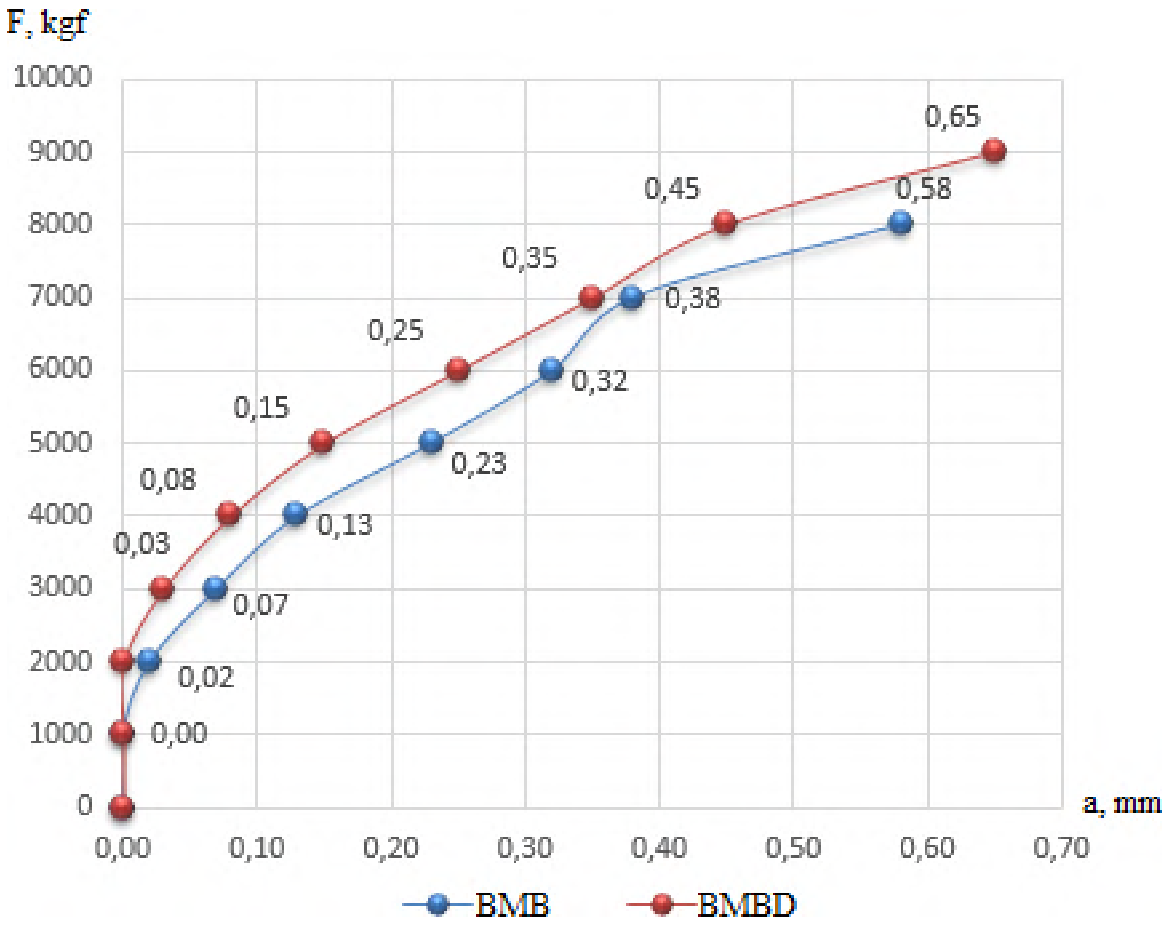

Figure 5. Graph of dependence of F – a of BMB and BMBD beams.

exceed 0.4 mm if the requirements for an acceptable appearance are established, and 0.8 mm in other cases. Since the series of BM beams with metal reinforcement in the tensile zone is taken as a control one for comparing the stress-strain state with beams of other series, for correct further analysis, we take the maximum permissible value of the crack opening width of 0.3 mm in accordance with [15].

The values of the width of the normal crack opening of the experimental beams given in table 4 indicate that 100% replacement of quartz sand with the small waste of plant protection products in the manufacture of concrete mixtures for reinforced concrete structures led to such results:

- BMD series beams have the same value of normal crack opening width as the control BM series beams – 0.09 mm, and do not exceed the maximum permissible value of 0.3 mm;
- beams of the BBD series reinforced with basalt-plastic reinforcement showed a larger value of the width of normal crack opening by 11.5% than the BB series, and exceeded the maximum permissible value by 93%;
- beams with hybrid reinforcement of the BMBD series showed a smaller value of the width of normal crack opening than the BMD series, by 7.9%, and exceeded the maximum permissible width by 16.7%. It should be noted that at a level of 60% of the destructive load, beams with hybrid reinforcement of the BMBD series had a normal crack opening width less than the maximum permissible width.

4. Conclusions

Studies of the use of small plant protection products waste in concrete mixtures for the manufacture of reinforced concrete structures show the following:

- there is no systematic control of annual volumes of plant protection products waste utilization;
- plant protection products waste has a chemically unstable and heterogeneous particle size distribution at each individual enterprise and requires additional research;
- the time period between experimental studies and publication of regulatory documents can be more than 10 years, which slows down scientific and technological progress;
- beams made of concrete on fine plant protection products waste showed comparable development of normal cracks with beams made of concrete on quartz sand under load;
- beams of BM and BMD series showed the same value of normal crack opening width – 0.9 mm, and beams of BMBD series, even less than the BMD series by 7.9%;
- at 70% of the destructive load, beams of BM and BMD series do not exceed the maximum permissible width of the normal crack opening, and beams of BMBD series do not exceed the maximum permissible width of 60%;
- there are no precautions regarding the use of concrete mixtures with 100% replacement of quartz sand with small waste of plant protection products for the manufacture of structures working in bending with metal, basalt-plastic reinforcement and hybrid reinforcement with metal and basalt-plastic reinforcement at the same time. The crack opening widths for all cases of reinforcement have similar values, regardless of the concrete composition. The difference does not exceed 11%, which is within the calculation error for this type of problem.

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Prospects for using composite preparations based on silica nanosols

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Abstract. Composite preparations were created for foliar feeding of winter wheat using obtained silica nanosols and lignin fugate after coals carbonization. Both laboratory and vegetative studies have confirmed the effectiveness of created preparations for foliar treatments of Cubus winter wheat (*Triticum aestivum L.*). When applied, the preparations enhanced the moisture-holding capacity of leaves, photosynthetic processes of the leaf apparatus, and biosynthesis of organic matter, compared to the control group. Additionally, the studied compositions increased the content of endogenous antioxidants, such as carotenoids in plants, and reliably contributed to the reduction of peroxidation processes in cell membrane lipids. Their use could increase the drought resistance of wheat plants.

1. Introduction

Many scientists have studied the nature of silicon in rice waste due to its various applications. The properties of ash formed from the husks depend on the burning method and thus determine possible applications in the future. Rice production waste contains high levels of silica (SiO_2) and other macro- and microelements, making it a promising source of silicon-containing preparations. These preparations, containing active silicon, have a significant effect on plant growth and development, increasing yield, product quality, and resistance to various stressors. This field is actively developing, with synthetic silicon-containing preparations being created for seed priming and foliar feeding of plants [1–6].

Previously, rice husk ash was obtained, which served as a starting material for the silica nanosols creation [7].

The industrial synthesis of silicic acid sols involves several methods, including neutralization of soluble silicates with acids, ion exchange, peptization of freshly formed silicic acid gels, electrodialysis, hydrolysis of silicon alkyl derivatives, dissolution of elemental silicon, and dispersion of fumed silica. Among these methods, the ion exchange method was first patented by Berdom [8] and has several modifications known in the literature. The main stages of synthesizing silica hydrosols with dense particles include such stages as: preparing the silicic acid solution, synthesizing the "seed" sol, particle growth, sol concentration, and changing the particle surface.

The amorphous structure of silicic acid sols remains intact for a long time, even when prepared through different methods. However, due to the development of stresses, the primary amorphous particles break down into many small crystalline particles that subsequently grow, aggregate, and form structures as the sol ages further. Amorphous silica (AS) has a lower degree of polymerization than quartz, which means that the differences in structure are only quantitative and not qualitative. One of the methods that can regulate the aggregative stability of sols and the adsorption capacity of the surface of silica particles is through adsorption modification of the surface. Modified sols synthesis significantly expands the potential applications of colloidal silica. The adsorption patterns of metal cations on silica at different pH and temperature have been studied in several works [8–10], and the process can be carried out in both acidic and alkaline environments. A technological process has been developed for obtaining concentrated and stable silica sols [11], which are stabilized with ammonium hydroxide. The amorphous silica use affects the phosphorus, calcium, potassium, and magnesium absorption and accumulation by plants [12]. It is known that AS strengthens the resistance of bread grains to various fungal diseases and can be used as an insecticide against corresponding insects. AS absorbs lipids from the cuticle of insects, leading to rapid dehydration of their bodies. Hydrophobic silica is more effective in this regard than hydrophilic silica. Silica aerogel, which is partially organophilic due to its preparation method, can inhibit the activity of weevils and grain weevils in granaries at a concentration of 0.05%. It has a longer protective effect compared to chemical insecticides and is non-toxic to animals and humans [12, 13].

The use of foliar sprays containing silicon compounds is a relatively new technique. Silicates were first used for spraying leaves in 1990 while spraying with stabilized silicic acid was introduced in 2003. Recently, spraying with silica nanoparticles has also been introduced. Silicates are effective as pesticides, while spraying with stabilized silicic acid has a positive effect on growth and yield, and also helps protect plants from stress. When silicon is absorbed by plant roots from the soil solution, it reaches a maximum of only 1-5% of the available number of forms. However, when vegetative plants are sprayed with an aqueous solution of silicon, the absorption level by the leaves is 30-40%. Therefore, the most effective way to use silicon-containing compounds is to treat vegetative plants with their aqueous solutions through foliar spraying [14].

Researchers have carried out experiments to determine the most effective sources of silicon (Si) for foliar application. It has been suggested that stabilized silicic acid is a promising compound for this purpose. The literature provides convincing evidence that certain cell wall components can cause SiO_2 deposition. Combining soil application and foliar spraying is an effective method for enhancing Si uptake by plants [14, 15].

Some authors have investigated that $Si(OH)_4$ (hereinafter referred to as Si for simplicity) acts as a “tonic agent”, priming plants, i.e. preparing protective reactions, which are then fully deployed at the onset of stress [16]. For example, salinity stress affects more than 800 million hectares worldwide – up to a third of all agricultural land and almost half of all irrigated land, which produces about a third of the world’s food. Drought stress, which shares many features with salinity stress, is even more widespread and destructive to agricultural production, especially in arid and semi-arid regions, which account for approximately 30% of the world’s land area. Both problems are predicted to be exacerbated by anthropogenic climate change [17]. There is a lot of evidence that silicon can improve the strength of cell walls and provide mechanical support to certain types of plants, specifically monocots and pteridophytes. However, less is known about how it affects dicots. Silicon can enhance suberization, lignification, and differentiation, resulting in improved structural stability. This is due to the binding of Si to the hemicellulose of the cell wall, which is especially useful during water deficiency [18]. Moreover, biosilification in plants involves the polymerization of silicic acid within the apoplast, which creates a barrier of amorphous silica. This barrier can help protect against both biotic and abiotic stresses by preventing pathogen infection and the penetration of toxic elements, such as Al, Cd, and Na [13, 19–21].

Si plays a vital role in reducing the transport of Na^+ to the shoots in the roots of salt-sensitive wheat. This happens because Si increases the binding of Na^+ to the cell wall in the root. Si can also regulate water transport by enhancing the accumulation of osmolytes which can affect the osmotic potential of cells. In addition, Si can reduce oxidative stress and membrane damage which can lead to an increase in root hydraulic conductance. Recent research has explored the concept of "seed priming" where exposure of seeds to Si for a few hours can strengthen plants against future stress events. Although studies have mostly focused on the resistance to biotic stress, seed priming has shown promise in conferring resistance to abiotic stress such as drought and salinity [22, 23]. In such studies, a decrease in proline, malondialdehyde (MDA), and Na^+ content was observed in seedlings treated with Si. However, more research is needed to understand the underlying mechanisms of Si's effects on seed priming [23].

The purpose of our work was to investigate the effect of foliar spraying with silicon-containing solutions on the growth and post-stress recovery of winter wheat under conditions of simulated moderate soil drought.

2. Materials and methods

2.1. The method of obtaining silica nanosols

Dispersion was carried out in an aqueous medium with a molar ratio of H_2O: SiO_2 = 1:0.047. The rotation speed of the disperser rotor was 15,000–20,000 rpm (Homogenizer, DAIHAN Scientific – Co.LTD, Korea). The ultrasound frequency used was 35 kHz, and the treatment lasted for 3 hours. White suspensions were obtained, from which large particles were removed by centrifugation. By varying the ratio of components, dispersions with a mass concentration of SiO_2 ranging from 1.13 to 10.63% can be obtained.

The surface morphology was investigated with atomic force microscope (AFM) NT-206 (Company with double liability "Microtestmachines", Belarus) equipped with standard sonde CSC37 and rigidity of console 0.3-0.6 N/m. The scan was run in a contact static mode at 10 mcm/s with a step of 0.3 nm.

2.2. Methodology of vegetation experiments

Determination of the effectiveness of created nanosols for foliar spraying of Cubus winter wheat plants was carried out in vegetation experiments. The experimental scheme is provided in the tables in the following section.

The vegetation experiment followed an established research methodology [24]. To prevent infections, 60% ethyl alcohol was used to treat wheat seeds for 15 minutes, followed by thorough washing with distilled water. The treated seeds were then germinated for one day at 26 ^oC in Petri dishes on moist filter paper with 50 seeds per cup. The sprouted grains were then planted in the soil. Winter wheat plants of the Cubus variety were grown in 5 kg vegetation pots filled with dark grey podzolic soil. The soil had an average content of macronutrients such as nitrogen, phosphorus, and potassium. Soil moisture in vegetation vessels was kept at 60% of its full moisture capacity and the plants were watered using Arnon-Hoagland solution. To create soil drought, watering was stopped for 18-day-old plants until the moisture content of the substrate was reduced by half. The air temperature during the experiment was maintained at 28–32 ^oC. Plants were grown under a light installation with a light intensity of 690 $\mu mol/(m^2{\cdot}s)$ and a photoperiod of 16/8 h (day/night). The experiment lasted for 58 days and was repeated 5 times. Phenological observations of the wheat plants were carried out during the experiment, and the impact of foliar spraying on their growth and development was also determined.

The thermogravimetric method was used to determine the mass fraction of dry matter in the plant material [24].

To determine the water-holding capacity index of leaves using A. Arland's method, the raw leaves were weighed using electronic scales. The mass of the leaves was then measured at 2, 4, 6, and 24 hours after the start of the experiment, along with the mass of dry leaves [25]. The experiment was repeated four times.

2.3. Determination of chlorophylls

In 58-day-old plants, the content of chlorophyll a, b and the total content of carotenoids were determined according to the Welburn method [26]. Dimethyl sulfoxide (DMSO) was used as a pigment solvent, which has some advantages over other solvents. Extraction of pigments was carried out for hours at a temperature of 67 °C in a thermostat. Spectrophotometric measurement of the optical density of solutions was carried out at wavelengths 665, and 649 (red region of the spectrum) and 480 nm (violet region). DMSO was used as a control.

The content of pigments was calculated according to the formulas:

$$C_a = 12.19 \cdot A \cdot 665\text{–}3.45 \cdot A \cdot 649, \quad (1)$$

$$C_b = 21.99 \cdot A \cdot 649\text{–}5.32 \cdot A \cdot 665, \quad (2)$$

$$C_{car} = (1000 \cdot A \cdot 480 \ --2.14 \cdot C_a \ --70.1 \cdot C_b)/220, \quad (3)$$

where C is the concentration of the corresponding pigment in the extract, μg/ml; A is the optical density measured at the appropriate wavelength for the chlorophyll a, b and carotenoids (car) determination.

To determine the concentration in mg of pigments per gram of crude substance, the following formula was used, taking into account the extract's dilution (C_p):

$$C_p = C \cdot 10 \cdot 3/(0.1 \cdot 1000 \cdot 0.5), \quad (4)$$

where C is the concentration of the corresponding pigment in the extract, μg/ml; 10 – extract volume, ml; 3 – volume of diluted extract, ml; 0.1 – weight of chopped raw leaves, g; 0.5 – volume of extract used for dilution, ml; 1000 – const (for recalculations of measurement units).

The amount of pigments (P) in mg per 1 g of dry matter of leaves was determined by the formula:

$$P = C_p/B, \quad (5)$$

where B is the content of dry matter, %.

The content of malondialdehyde (MA) in plant leaves was determined by the photocolorimetric method using thiobarbituric acid [27].

The experimental results were processed by the variational statistics method using the Student's test [28]. Average arithmetic values were presented in tables. Statistical data was analyzed with Microsoft Excel.

3. Results and discussion

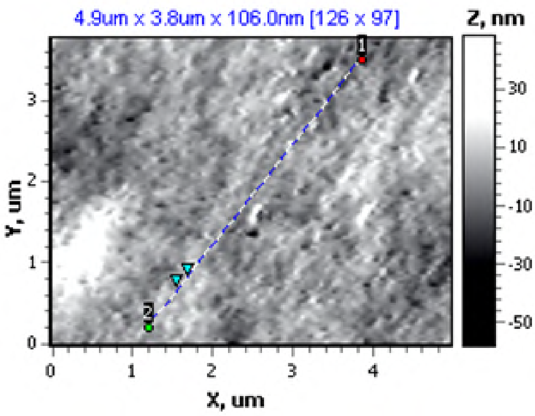
3.1. Characteristics of obtained silica nanosols

Silica nanoparticles were obtained using two methods: high-speed dispersion with ultrasound processing (mechanical method) and nanosol synthesis by hydrolysis of tetraethoxysilane. It's important to note that silica particles tend to aggregate in a liquid medium to form agglomerates. Moreover, as the particle volume decreases, the effect of agglomeration becomes more pronounced due to the size effect. For instance, if the particle size is 10.3, 10.2, and 10 nm, the share of the interface increases from 0.3 to 3 and 30%, respectively. Therefore, dispersing silica into a sol consisting of discrete particles is quite challenging. High-speed dispersion damages the skeletal structure that is formed by silanol groups (Si–OH). Ultrasound treatment is more effective in this regard, as it creates cavitation shock waves that can break down large particles.

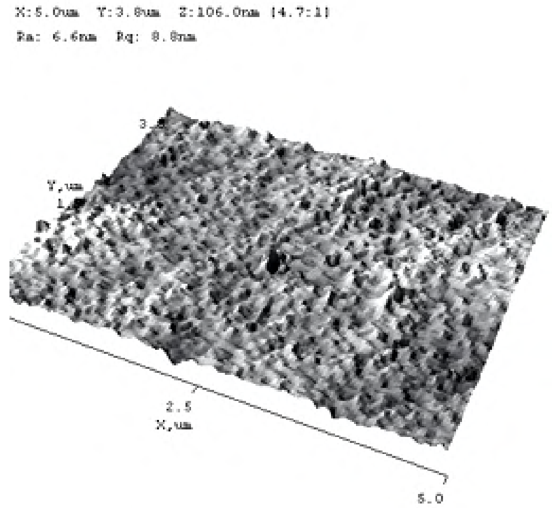
The synthetic method involves hydrolyzing tetraethoxysilane in an acidic environment (aqueous ethanol pH 1.5-2) at a temperature of 42 °C for 2 hours. This ripens the nanosol, which is then diluted with water at a ratio of 1:8. The solution is then treated with alkaline reagents or anionites. The concentration of the nanosol is 10.1%. To estimate the size of the obtained particles, a comparative AFM of the samples was carried out.

In figure 1(a), you can see a 2D image of a sample's surface obtained through high-speed dispersion with ultrasound processing. The scan size of the image is 4.9 μm x 3.8 μm, and there is a section line marked as 1-2. The surface roughness of the sample is Ra = 6.6 nm which is shown in figure 1(b). Additionally, the cross-section analysis of section 1-2 (figure 1(c)) reveals that the surface on this cross-section is made up of particles having a size of 8.1, 6.4, and 8.7 nm.

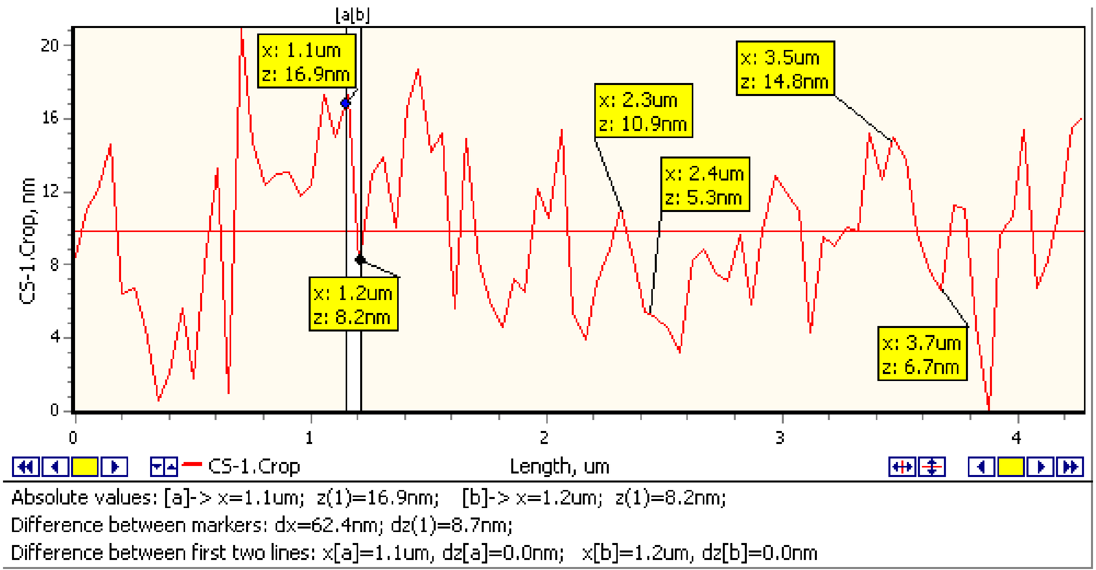
In figure 2(a) a 2D image with a scan size of 2.4 μm x 2.3 μm is shown. This image displays the surface of the nanosol, which was obtained by hydrolyzing tetraethoxysilane. The cross-section



(a)



(b)



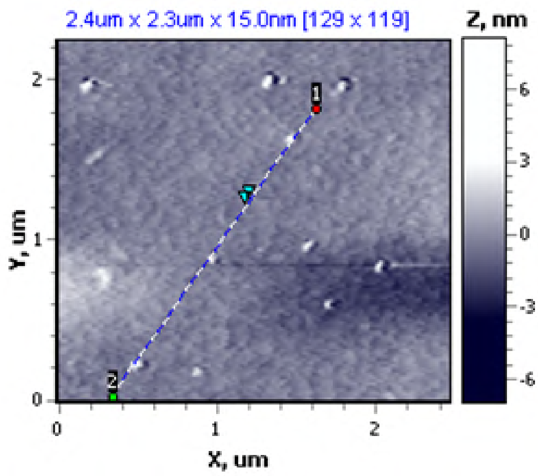
(c)

Figure 1. 2D (a) and 3D (b) images of the surface of the sample obtained by high-speed dispersion with ultrasound processing with shown cross-section line 1–2 and the profile of the last one (c).

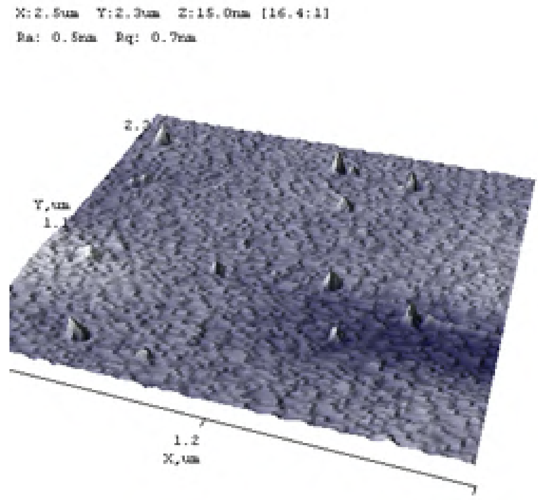
line 1-2 is also visible in the figure 2(a). The surface roughness is minimal at $Ra = 0.5$ nm, as shown in figure 2(b). A closer analysis of the cross-section profile 1-2, as seen in figure 2(c), reveals that the surface is formed by particles particles with sizes ranging from 0.3-0.8 nm.

After analyzing the AFM data of two nanoparticles samples, it can be concluded that larger and more aggregated nanoparticles are formed in the case of dispersion. On the other hand, nanosol obtained by the hydrolytic method is made up of smaller particles with sizes an order of magnitude smaller than those in the case of dispersion. These smaller particles are less aggregated and more discrete.

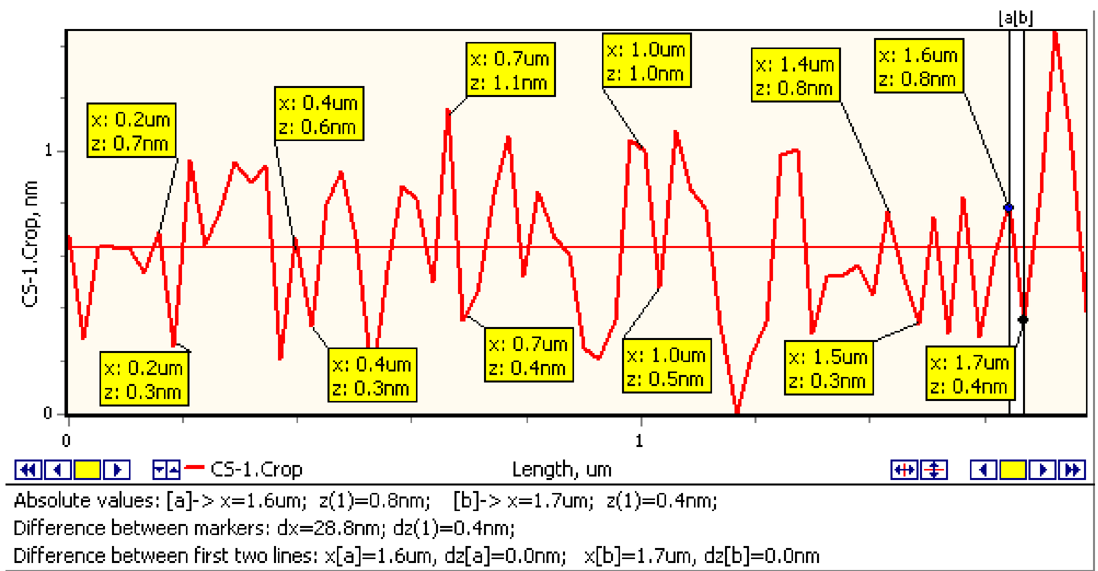
The obtained nanosols were used to create biologically active composites with metal salts, humates and lignohumates (LH).



(a)



(b)



(c)

Figure 2. 2D (a) and 3D (b) images of the surface of the sample obtained by hydrolysis of tetraethoxysilane with shown cross-section line 1–2 and the profile of the last one (c).

3.2. Study of the effectiveness of the use of Si-nanosols for foliar treatments of winter wheat
Foliage is an important indicator characterizing the growth processes of plants, which in the future directly affects the yield. The process of photosynthesis and, accordingly, the formation of organic substances, which is the basis of productivity, depends on the leaf's formation and development.

Determination of the created products' anti-stress effect based on silica nanosols, a potassium silicate (lignin centrate) solution for foliar treatments, was carried out in a vegetative experiment with winter wheat of the Cubus variety. In the vegetation experiment, soil moisture deficiency was simulated three times (soil moisture was maintained at the (30±5)% level of the total soil moisture content for two weeks).

Based on the analysis of the results presented in table 1, it was found that treated plants did not differ in biomass when compared to plants grown under favourable conditions. When modelling under regulated conditions of soil moisture deficit at the level of (30±5)% of the total moisture content in the tillering phase, the experimental wheat plants reliably differed from the control ones in terms of productivity. The mass of the ground part of 100 plants in the experiment had a range of 10.6 g (in the control group) to 12.15 g (when using the composition with potassium dihydrogen phosphate) after three treatments of plants with compositions based on silica nanosols. Other versions of the experiment demonstrated an increase in the mass of the ground part by 10-12%. On the other hand, the weight of the roots of the experimental wheat plants (2.9–3.01 g) was almost no different from the control (2.9 g). The treatment of plants with Si-LH, Si-KH_2PO_4, and Si-nanosol resulted in the highest values of root mass (3.0-3.01 g). Essentially, foliar fertilization with Si-containing compositions led to a slight increase in the processes of organic matter synthesis and nutrient translocation in plants, even under insufficient moisture in the conditions of the vegetation experiment.

It should be noted that in the experiment, the aqueous solutions application of the studied compositions through foliar feeding resulted in an improvement in the linear dimensions of wheat plants, including the length of their roots and above-ground parts. In particular, treating the leaves thrice with nanosol solutions stimulated the growth of the above-ground parts of the plants. Compared to the control, an increase in the length of the leaves by 6-7 cm was observed in the variant using nanosol Si-HA (humic acids) + ME (microelements) and Si-LH. The addition of potassium humate with biogenic ME and LH to the composition of Si-nanosol

Table 1. The effect of foliar fertilization with silicon-containing compounds on the biometric parameters of experimental plants and the bioproductivity of 58-day-old plants of winter wheat of the Cubus variety in a vegetation experiment.

	Variants of foliar feeding	100 plants weight, g (a.d.m.)			Length, cm	
		above-ground part	root system	whole plants	above-ground part	root system
1	Control	10.64±0.39	2.90±0.17	13.54±0.56	57.0±2.5	25.4±1.3
2	SiO_2-nanosol, 0.006 (%)	10.93±0.33	3.02±0.18	13.95±0.51	61.0±2.4	26.3±1.5
3	SiO_2-HA, 0.006 (%)	11.74±0.31	2.99±0.18	14.73±0.49	63.5±2.5	26.9±1.7
4	SiO_2-LH, 0.006 (%)	11.91±0.34	3.00±0.14	14.91±0.48	62.7±2.4	27.3±1.9
5	SiO_2-HA+ME, 0.006 (%)	11.86±0.32	2.85±0.15	14.71±0.47	64.4±2.6	27.8±1.8
6	SiO_2-KH_2PO_4, 0.006 (%)	12.15±0.36	3.01±0.18	15.16±0.54	63.7±2.2	26.1±1.6
7	SiO_2-Cu-NH_3, 0.006 (%)	12.04±0.39	2.94±0.17	14.98±0.56	63.9±2.8	25.3±1.3
8	$K_2SiO_{3centrate}$, 0.006 (%)	11.02±0.36	2.92±0.21	13.94±0.57	58.06±2.2	26.7±2.1

likely contributed to the stimulation of growth processes in the experimental plants of Cubus winter wheat.

A mandatory condition for the growth and development of plants, resistance to the influence of adverse environmental factors is their ability to maintain a certain level of water balance. Plants react to moisture deficit with a complex response, which includes perception of stressor action, initiation of signal transduction pathways and physiological and biochemical changes in the cell. Under the influence of drought, the formation of reactive oxygen species increases in chloroplasts and mitochondria. Therefore, exogenous influences inducing the antioxidant system are considered methods of increasing the drought resistance of plants. Even with a slight stress on the water balance of plants caused by drought, the normal course of metabolic processes is disturbed, as a result of which the productivity of plants decreases [29].

The water-holding capacity was studied according to the method of A. Arland, which is based on the calculation of the rate of water loss during the withering of the shoot by weighing it at regular intervals. The obtained data on the change in shoot weight characterize the level of water-holding capacity.

Statistically probable indicators of the water-holding capacity of winter wheat leaves of the Cubus variety under the influence of foliars (after 2, 4, 6, 24 h) in the tillering phase are given in table 2. Two hours after cutting the leaves of experimental plants of the variants, where foliar spraying with certain solutions was carried out, lost 14.5–21% less water compared to the control. Similar results were also obtained after 4 and 6 hours. Thus, water loss decreased by 15–21% compared to the control, where spraying was carried out with water. The amount of water lost by the leaves of plants of the control variant was greater by 20 and 21% compared to the indicators in the variant where a solution of nanosol with potassium dihydrogen phosphate was used three times. Obviously, more osmotically active substances accumulated in the leaves of plants of the specified variant due to foliar fertilization. It is worth noting that the composition of the two test solutions contains potassium (in variants 6 and 9), which is an osmotically active cation [30, 31] and provides reliable moisture-retaining protection, which affected the indicators of moisture loss in the vegetation experiment with winter wheat of the Cubus variety. After 24 h, the leaves lost a significant amount of water and the probable difference between the control and the experimental variant was not determined. The analysis of the obtained indicators shows that under the influence of solutions for foliar treatments, the leaves of experimental plants of winter wheat lost less water compared to the control.

According to leading physiologists, the content of photosynthesis pigments (PP) in plants can be a more informative indicator of the toxicity of seed or leaf treatments. table 3 shows the

Table 2. The effect of foliar fertilization on the water-holding capacity of winter wheat leaves of the Cubus variety (amount of water lost in %) in the tillering phase, M±m, $n = 12$.

	Variants of foliar feeding	2 h later, (%)	4 h later, (%)	6 h later, (%)	24 h later, (%)
1	Water, control	28.05±1.49	43.41±2.07	55.68±2.29	69.7±2.71
2	SiO_2-nanosol, 0.006 (%)	24.43±1.53	36.27±2.02	44.78±2.31	68.4±2.4
3	SiO_2-HA, 0.006 (%)	24.74±1.62	35.85±2.08	45.70±2.32	68.5±2.5
4	SiO_2-LH, 0.006 (%)	23.92±1.68	36.86±2.17	43.83±2.33	68.7±2.4
5	SiO_2-HA+ME, 0.006 (%)	26.96±1.72	36.05±2.21	42.88±2.72	67.7±2.6
6	SiO_2-KH_2PO_4, 0.006 (%)	22.43±1.66^a	34.92±2.34^a	40.88±1.32^a	67.8±2.2
7	SiO_2-Cu-NH_3, 0.006 (%)	24.84±1.59	35.95±2.26	41.83±1.6^a	69.2±2.0
8	$K_2SiO_{3centrate}$, 0.006 (%)	26.44±1.31	36.73±2.41	43.37±2.52	67.7±2.4

^{a} – the difference is probable compared to the control at $p \leq 0.05$.

results of determining the effect of foliar treatments of Cubus wheat with the studied compounds based on silica nanosols on the content of chlorophyll, total carotenoids and malondialdehyde (MDA) in the leaves of 58-day-old plants. The data in this table show that the PP content in the experiment varied depending on the options for foliar treatment of plants. Thus, the use of Si-containing preparations in the experiment contributed to the accumulation of a larger (by 5–7.5%) amount of chlorophyll in plant leaves compared to the control. The greatest increase in the content of chlorophyll a was observed in the version using potassium dihydrogen phosphate or copper-ammonia complex. More significantly, the fertilization variants affected the formation of chlorophyll b. Its content increased by 8–14% compared to the control, and the greatest effect was noted in the option with three times the use of compositions with potassium dihydrogen phosphate and copper-ammonia complex – an increase of 12.7 and 14% respectively.

Table 3. The effect of foliar fertilization on the water-holding capacity of winter wheat leaves of the Cubus variety (amount of water lost in %) in the tillering phase, M±m, $n = 12$.

	Research options	Chlorophyll content, mg/100 plants			Total carotenoids content, mg/100 plants	MDA content, nmol/g of raw leaf mass
		a	b	a+b		
1	Control	53.1±1.7	15.8±0.4	68.9±2.1	8.2±0.3	79.9±3.4
2	SiO_2-nanosol, 0.006 (%)	54.4±1.7	15.1±0.5	69.5±2.2	8.7±0.4	71.1±3.9
3	SiO_2-HA, 0.006 (%)	55.0±1.8	16.9±0.6	74.9±2.4	8.9±0.5	72.0±3.8
4	SiO_2-LH, 0.006 (%)	55.8±1.8	17.1±0.3	72.9±2.1	9.2±0.4	69.5±3.7
5	SiO_2-HA+ME, 0.006 (%)	54.1±1.7	16.6±0.7	70.7±2.4	9.1±0.3	70.3±3.8
6	SiO_2-KH_2PO_4, 0.006 (%)	56.4±1.8	17.8±0.6	74.2±2.4	9.5±0.4	66.4±3.3
7	SiO_2-Cu-NH_3, 0.006 (%)	56.9±1.9	17.0±0.6	74.9±2.5	9.8±0.2	65.9±3.4
8	$K_2SiO_{3centrate}$, 0.006 (%)	54.8±1.7	15.9±0.6	70.7±2.3	9.1±0.3	71.0±3.7

This also affected the indicator of the sum of chlorophylls (a+b) – an increase of 8–11% compared to the control. Variants of foliar fertilization with compositions based on silica nanosols with potassium dihydrogen phosphate or a copper-ammonia complex provided the greatest increase in the amount of chlorophyll – by 11%. It should be noted that the treatment of plants with the created compositions significantly contributed to the increase in the biosynthesis of endogenous antioxidants – general carotenoids. The highest content of carotenoids in leaves was observed with the use of foliar nanosols with potassium dihydrogen phosphate and with Cu-NH_3 – an increase compared to the control by 16 and 20%, respectively. With the use of lignin fugat, the content of carotenoids exceeded the reference values by 11%. The introduction of humic and lignohumic components into the composition of the nanosol provided an increase in the indicator by 9–11%. Obviously, the change in the number of carotenoids in our experiments was associated with a lower sensitivity of the enzymes of their synthesis to the components of the preparations, as well as with the active role of the specified pigments in the neutralization of reactive oxygen species (ROS).

By increasing the content of endogenous antioxidants – carotenoids in plants, the studied compositions contributed to a 12-17.5% decrease in the formation of MDA in plant leaves – an intermediate product of lipid peroxidation, mainly lipids of cell membranes. A decrease in the content of MDA in the leaves of experimental plants of winter wheat was more significantly observed in the version using Si-Cu-NH_3 – by 17.5% and with Si-potassium dihydrogen phosphate – by 17%. The use of aqueous solutions of lignin centrate and silica nanosol led to a decrease in the MDA index by only 11%.

Quantitative changes in lipid peroxidation in the experiment indicate that foliar fertilization of winter wheat of the Cubus variety with Si-containing solutions has a stress-protective effect on plants that were grown in conditions of insufficient moisture supply. This can probably be explained by the initial non-specific reaction of the variety to stress (insufficient moisture supply) due to the passive adaptation of the plant.

The results of the vegetative experiment allow us to state that the created compositions based on silica nanosols exhibit antioxidant properties – they ensure a decrease in the content of malondialdehyde in the leaves of plants – an intermediate product of the undesirable peroxidation process of lipids, mainly lipids of cell membranes, which negatively affects the functioning of cell membranes and, probably, on growth processes. The use of Si-containing compounds for foliar feeding helps to increase the activity of the photosynthetic apparatus, and by reliably increasing the content of total carotenoids in the leaves, exogenously strengthens the antioxidant system of plants, which is important for increasing the resistance of plants to stresses. Thus, they increase the resistance of plants against such stress as insufficient moisture supply.

According to the integral evaluation of the obtained results, spraying of vegetative plants of winter wheat (three times) with preparations based on silica nanosols and lignin fugate did not cause burns on the leaves of winter wheat plants of the Cubus variety and provided protection of plants from the negative impact of stressful growing conditions – insufficient moisture supply.

4. Conclusion

The analysis of the obtained results of the vegetation experiment gives reason to conclude that the compositions of silica nanosols with lignohumates, potassium dihydrogen phosphate, and copper-ammonia complex are effective for carrying out foliar spraying in conditions of insufficient moisture supply of plants. The use of these compositions for foliar feeding of Cubus wheat activates the work of the photosynthetic apparatus of plants, suppresses the processes of peroxidation of lipids of cell membranes, and provides higher indicators of water-holding capacity. Thus, under stressful conditions of winter wheat plant growth and development, three-fold foliar treatment with products created based on silica nanosols ensures a reduction in the negative effect of the stress effect of adverse environmental factors.

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Current state and prospects of red mud utilisation: A review

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Current state and prospects of red mud utilisation: A review

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Abstract. The article is devoted to the urgent problem of utilisation of red mud (RM) – a by-product of bauxite ore processing in the process of aluminium production. The acuteness of the problem is increased by the negative influence of red mud on the environment due to its high alkalinity of its pulp (pH = 9-12) and fine dispersibility. The article characterises the main properties of RM, reveals the essence of the most effective method of its storage today – dry stacking. Due to the presence of high content of iron oxide and such metals as Al, Ti, Y, Ce, etc. in the composition of RM, it is a valuable complex man-made raw material. The analysis of modern technologies of RM processing has shown that the important tasks in its utilisation are the processes of dehydration and disinfection. The first one is most successfully solved by using filter presses, the second one – by adding lime to the sludge washing system. Technologies for extraction of valuable components from RM can be divided into two groups – pyro- and hydrometallurgical. The most promising solution to the problem of effective integrated waste-free processing of RM is a rational combination of these two processes.

1. Production and storage, composition and properties of red mud

Red mud, sometimes called bauxite residue, is a by-product of alumina production, the main product of which, alumina, obtained from the processing of bauxite ore using the Bayer hydrometallurgical process, serves as a raw material for the production of aluminium. Global production of this valuable metal, which is widely used in many industries, is continuously increasing. In 2022, global aluminium production rose by 2.2 % to 69 million tonnes. Aluminium production is expected to grow at an average annual rate of 6.1 % until 2029 [1]. The largest consumers of refined aluminium are East Asian countries, where aluminium consumption increased from 7.1 million metric tonnes to over 40 million metric tonnes in 15 years (2005 – 2020). The world's largest consumer of refined aluminium is China.

The increase in aluminium production is accompanied by an increase in alumina production (figure 1) and its by-product red mud, which yields about 1.2 tonnes per tone of alumina produced [2] and can range from 900 to 1500 kg/t [3]. The specific yield of red mud depends on the quality of feedstock and the perfection of alumina processing technology. The higher they are, the lower the yield of the by-product – sludge.

The world production of red mud in 2017 was $\sim$ 150 million tonnes, and its total reserves worldwide are estimated by different data from 2.7 to 4 billion tonnes [3–5].

Due to the current lack of effective technologies for mud processing, in most cases it is simply stored in isolated areas – mud storages – tanks with a height of 30 – 50 metres. They occupy

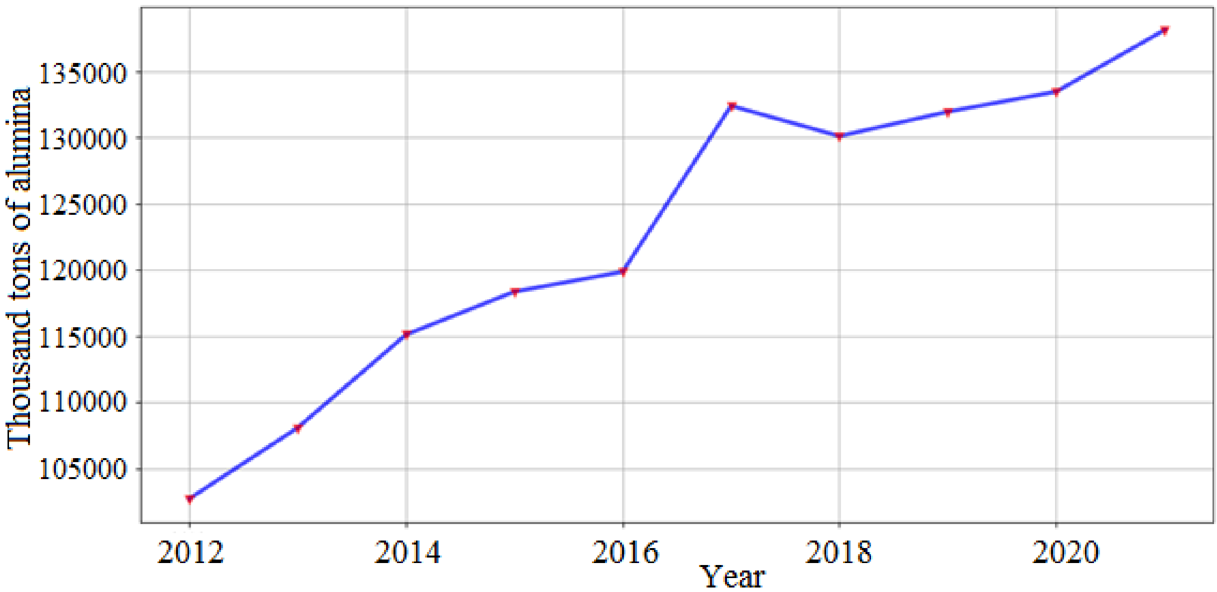

Figure 1. Global alumina production in 2012-2021.

10-50 hectares of land area and contain tens of millions of tonnes of mud [3]. Construction of new mud storages and maintenance of old ones requires large expenses. In addition, mud storages serve as a source of environmental pollution (including due to the risk of mud storages rupture, as it happened in Hungary in 2010 (figure 2) [3]), and the lands on which mud storages are arranged are removed from useful land use.

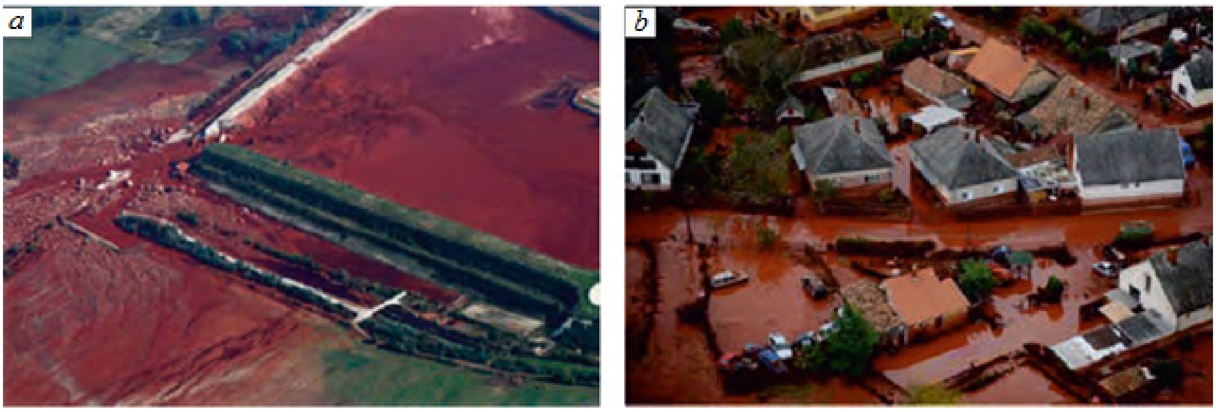

Figure 2. Environmental disaster in Hungary: (*a*) breach of the red mud storage dam; (*b*) flooding of Kolontar village with mud.

A specific Guide to the Sustainable Management of Bauxite Residues [2] has been developed, which explains the life cycle of stored red mud and, based on relevant case studies, shows how stakeholders can play an active role in its sustainable management.

Alumina refineries around the world are experiencing difficulties in the storage and utilisation of red mud. Dry stacking is currently one of the most popular methods of red mud disposal. This method is a safer and more stable disposal of red mud with lower land costs compared to the creation of sludge storage facilities. When using the dry stacking method, covering the discharged red mud reduces the risk of environmental contamination. Among eighty four alumina refineries worldwide, seven refineries discharge red mud into the sea due to insufficient alumina [5].

Red mud is a residue of bauxite leaching with $NaOH$ solution, therefore its Na_2O content can be up to 12.36 %. The chemical composition of the sludge varies considerably depending on the composition of the initial bauxite and leaching parameters. The content of the main components of red mud from different plants (and approximate average value) is as follows, %: 6.8 – 65.7 (41) Fe_2O_3; 2.12 – 33 (17) Al_2O_3; 0.6 – 23.8 (10) SiO_2; 0.19 – 46 (9) CaO; 2.5 – 22.6 (9) TiO_2; 0 – 12.36 (5) Na_2O; 1 – 30 (10) moisture, volatile, rare earth metals (REM). The red mud contains significant amounts of La, Ce, Pr, Nd and other REM, the total content of which is in the range of 506 – 2500 g/t, including 90 – 110 g/t Sc_2O_3 [3].

The phase composition of red mud from different plants also varies greatly. The most typical minerals are hematite (present in the amount from 7 to 29 % practically in all sludges), goethite, betite, gibbsite, anatase, rutile, ilmenite, perovskite, quartz, as well as complex aluminosilicates such as sodalite, cancrinite and kaolinite [3].

The particle size of red mud is very small and ranges from 0.1 to 200 microns [3] with an average particle size of less than 10 microns and density of 3.0 – 3.8 g/cm^3. Specific surface of particles is in the range of 10 – 25 m^2/g and depends mainly on the temperature of processing of initial raw material [4].

Another characteristic of red mud, which makes its utilisation difficult, is the high alkalinity (pH 10-12) of its pulp due to its sodium content, which makes it corrosive [4].

2. Preparation for use and main directions of red mud utilisation

An important place in the technology of utilisation and possible recycling of red mud is occupied by the dewatering operation, which provides not only effective storage of sludge, but also its shipment to the consumer, as well as preparation for subsequent recycling processes. Several methods of sludge dewatering can be distinguished, which have different degrees of applicability (figure 3) [3].

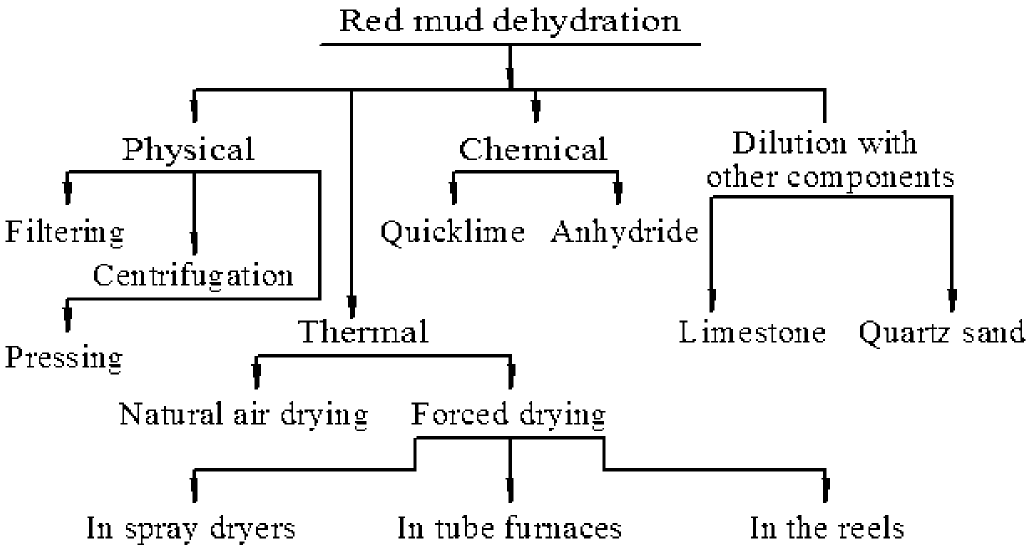

Figure 3. Methods of red mud dewatering.

The most effective way of dewatering is filtering, which, due to the possibilities of modern equipment, allows to obtain sludge with low moisture content. Preparation of red mud using belt filter press FRAKM-25 allows to receive a cake with humidity about 25 %, which has the required transportability properties. Positive results of tests on a pilot plant with a capacity of 20 thousand tonnes/year (figure 4) served as a basis for the construction of a shipping complex designed for the full capacity of the alumina refinery [6]. The experience of operation of the complex of red mud dewatering by filter presses with a capacity of 500 – 700 thousand tonnes/year has shown that this method is optimal for today [3].

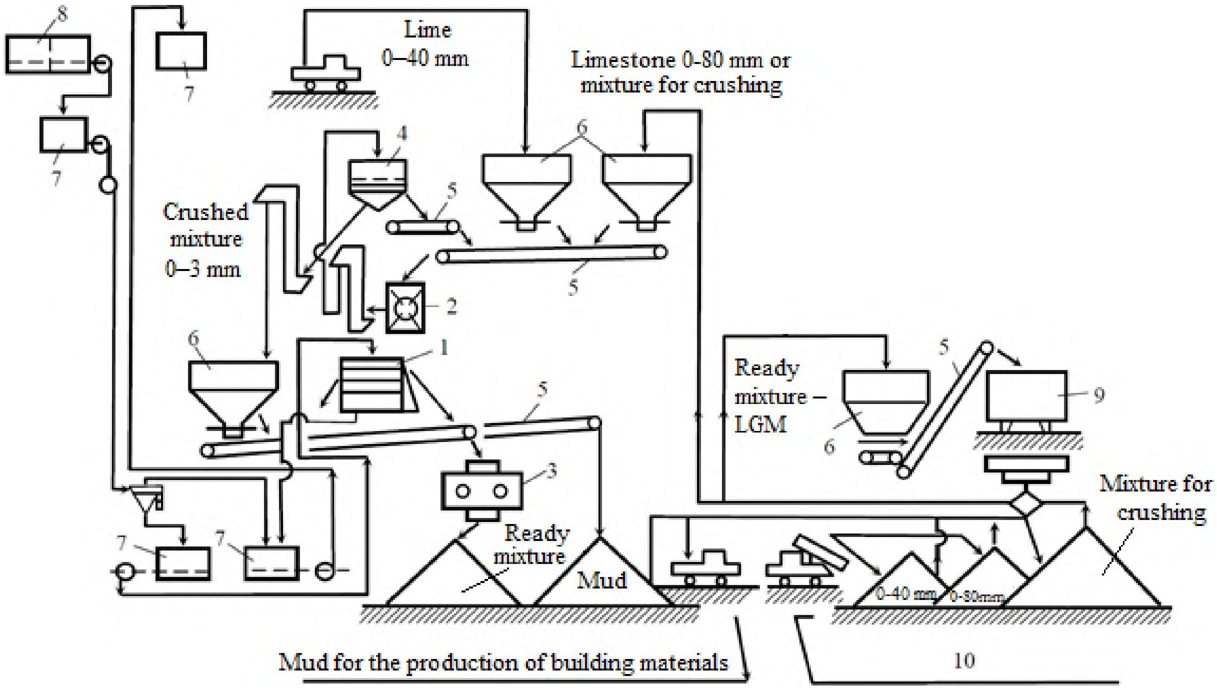

Figure 4. Apparatus-technological scheme of pilot plant for production of transportable commercial red sludge with capacity of more than 20 thousand tonnes per year: *1* – filter-press; *2* – crusher; *3* – mixer; *4* – screen; *5* – conveyors; *6 – 8* – alumina shop washer; *9* – railway wagon; *10* – stack.

Experimental studies of drying kinetics after filter press of mud of Greek origin using thin-layer modeling have established the values of effective moisture diffusion in the temperature range 50-250 $^{\circ}C$, as well as the value of activation energy of drying of red mud equal to 28.133 kJ/mol [7].

Depending on the composition and physicochemical properties of mud, various methods of its neutralization and processing are used: chemical, physicochemical, thermal and their combinations [8].

The most common technologies for regeneration of alkali from red mud back to the Bayer process are methods of its removal by adding lime to the washing system or after it. It is known that the addition of lime to the slurry, which includes slightly alkaline wash water, can remove 70 – 80 % of alkali [3]. Studies of alkali regeneration from red sludge by adding lime allowed to establish the optimal parameters of the process: temperature 80 – 95 $^{\circ}C$; L:S from 3:1 to 8:1; dosage of lime 1.5 – 4.0 mol per 1 mol Na_2O sludge and duration of treatment 1.5 - 3.0 hours [3]. In the process of testing the red mud containing, %: 13.36 Al_2O_3; 45.52 Fe_2O_3; 2.8 Na_2O, after washing in a stirrer at L:S = 3:1 and temperature 90 $^{\circ}C$ for two hours was mixed with lime at the rate of 3 mol CaO_{act} per 1 mol Na_2O sludge at the duration of treatment 1,5 - 3,0 hours. The obtained weak alkaline solution was directed to the Bayer process of the main alumina production.

Neutralization of red mud by removal of alkaline film is possible with the help of aqueous hydrochloric acid solution [9]. As a result of the acid reagent, the mass fraction of water-soluble components in the heterogeneous system decreases, while the average particle size increases from 1.6 to 2.0 μm and specific surface area from 23.7 to 25.7 m^2/g as a result of adhesive interaction. The ratio between particle size fractions of red mud practically does not change.

Due to its rich material composition, red mud should be considered not only as a by-product of alumina production, but also as a secondary technogenic raw material requiring complex processing to obtain marketable products. Calculations have shown that red mud contains 44 % of chemical exergy of bauxite and is produced at a mass ratio of (2-3):1 to metallic aluminium. The relatively high exergy embodied in red mud is due to the significant amount of residual minerals (hematite, anatase, quartz) originally present in bauxite [4].

The most common methods of sludge utilisation are thermal. Fire treatment allows complete neutralization of combustible components of sludge with obtaining harmless combustion products and ash residues consisting of metals and their oxides. Along with direct incineration, thermal methods are often a part of complex technologies of sludge neutralization and utilisation. In these technologies, thermal treatment either precedes or follows a physicochemical or chemical process for the extraction of valuable components from the sludge. Such complex methods extract iron from sludge, recover catalysts containing nickel, palladium, platinum, copper, tellurium and other valuable metals, as well as extract these metals from spent catalysts [8].

For firing of red mud, drum furnaces with countercurrent thermal treatment system are used. For the same purposes cyclone furnaces with upper gas outlet are used, calcination in which provides complete neutralization of sludge due to combustion of toxic organic substances and capture of valuable mineral products [8].

The hydrometallurgical process for the extraction of alumina and sodium oxide from red mud is used in the calcification-carbonisation method (CCM), which was proposed to increase the scale of integrated sludge recycling [10]. First, the alkali in the red mud is removed by adding lime, then the calcined residue (including hydrogranate) is decomposed with carbon dioxide, finally, the carbonised residue is decomposed with aqueous alkali at low temperature and a new structure of red mud based on $CaSiO_3$ and $CaCO_3$ is obtained.

In many works, such as [11–13], pyrometallurgical methods with the production of pig iron (ferrosilicon) and alumina slags are characterised as the most efficient. A distinctive feature of pyrometallurgical methods is their multistage nature.

A waste-free process of red mud processing (figure 5) was proposed, which includes obtaining carbon-containing pellets from sludge and semi-coke, their reducing roasting using a rotary hearth furnace, smelting of the reduced pellets in an electric arc furnace to produce metal and desulphurising flux [12]. This process combines the methods of alumina and steel industry, which can not only solve the problem of red mud processing in alumina refinery, but also help steel mills to reduce the production cost.

One of the variants of complex processing of red mud is its reductive smelting in a mixture with limestone in an electric furnace to produce pig iron and alumina-calcium slag. The alumina-calcium slag can be processed into alumina and cement.

Another use of red mud is to use it directly as an additive in the production of various products. There are solutions to use red mud in the production of cement, bricks, ceramics, fire-resistant concrete, foundry-moulding mixtures, sewer pipes, glass fibre, for soil consolidation in road construction, as a coagulant for wastewater treatment, as the main component of a complex binder for mine workings and for other purposes. Nevertheless, so far few of these proposals have received practical use in life [8].

For example, Bayer sludges are plastic due to their aluminous-iron composition and high dispersibility, so in mixtures with clays they can be used in the production of ceramic products. The optimal composition of silicate bricks is as follows, % (by weight): sand – 76.2; bauxite

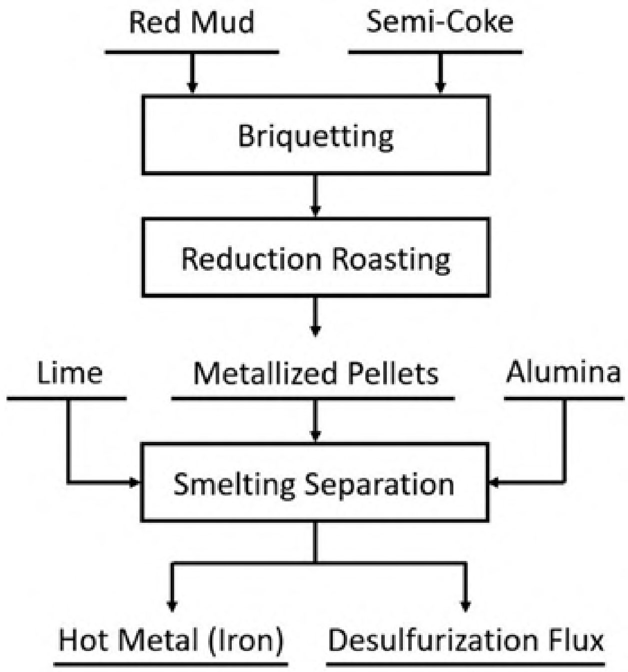

Figure 5. New process of red mud processing.

sludge – 18.8; lime – 5. Bayer sludge can also be considered as a raw material source for the production of complex iron-aluminium containing coagulant. The production of such a coagulant is based on sulfuric acid decomposition of bauxite sludge to form a mixture of trivalent iron sulfate and aluminium sulfate [14].

The possibility of using red sludge in the form of a slurry with the ratio L:S about 5:1 for purification of industrial waste gases from sulphur compounds and as a modifying additive used in the technology of slag granulation has been established [15,16]. Studies of sorption properties of red mud showed its high absorption capacity in relation to sulphur compounds, which is due to the ratio of calcium, magnesium and aluminium oxides to silicon oxide, so it can be an alternative to expensive lime and limestone. The proposed technology has a great advantage over other granulation methods using calcium oxide and calcium hydroxide. The addition of red mus is not only a desulphuriser, but also serves as a valuable component for slag processing with further application in the construction industry.

Among various methods of using red mud, its potential as a catalyst for various chemical processes has proved to be very successful. The presence of many valuable metals in red mud, in particular iron, makes it a suitable catalyst for energy production by such processes as pyrolysis, hydrotreating, transesterification and H_2 production from biomass and other raw materials (figure 6) [17].

At the same time catalyst on the basis of red mud can be prepared by various methods: acid treatment, saturation with active metals, calcinations, oxide reduction, etc.

A special problem hindering the introduction of red mud processing technologies is its increased radioactivity inherited from bauxite and caused by the presence mainly of thorium and to a lesser extent uranium. The methods of extraction of radioactive metals from red mud offered today are not economically efficient, and the most promising are complex technologies of red mud processing, allowing to extract rare, rare-earth and radioactive metals simultaneously [18].

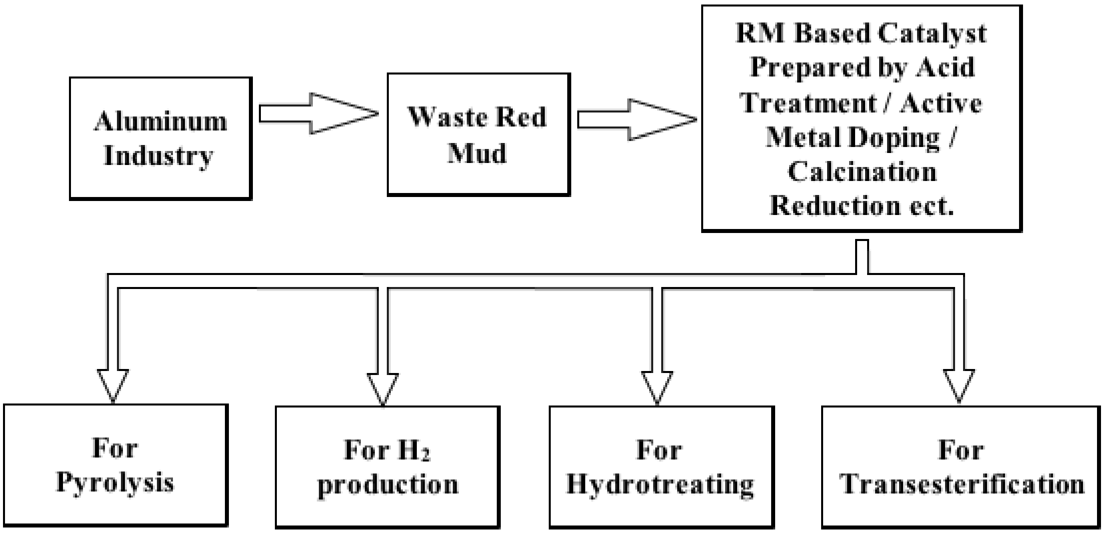

Figure 6. Scheme of possible directions and methods of using red mud as a catalyst for energy production by means of chemical rocesses.

3. Metallurgical orientation of red mud processing

The increased content of iron, aluminium and titanium oxides makes red muds attractive for extraction of these metals. It is established that as a result of red sludge recycling it is possible to obtain pig iron, aluminium, concentrates of rare metals.

As a result of technological modeling the technological (figure 7) and apparatus schemes of joint leaching of red mud and oily rolled scale were proposed [19]. A distinctive feature of the technological scheme, which increases the efficiency of solvent utilisation, is a closed water cycle with compensation of moisture losses with sludge and spent filtrate. The primary treatment of scale is proposed to be carried out at the place of its receipt, and the secondary (together with red mud) – at the enterprise processing bauxite. The technological scheme, in addition to those presented in fig. 7, includes the following operations: treatment of oily scale with industrial water at the ratio of solid to liquid 1:(45) and temperature $90 - 100$ $°C$; sedimentation of the pulp with drainage of the upper oil layer and subsequent activation of the pulp; oil utilisation by dewatering and filtration; processing of the pulp with separation of the washed dewatered scale in a centrifuge; transportation of scale for joint processing with red mud; introduction of washed scale into the reactor with mixing with red mud at the mass ratio of scale and mud in the mixture corresponding to the requirements of the subsequent processing of the solid filtration product, i.e. blast furnace process [9].

As a result of stepwise leaching of the main valuable components of red mud – iron and aluminium oxides – using hydrochloric acid, the following results were obtained [20]. At the stage of pre-leaching under optimised conditions using HCl (0.2 M) at room temperature for 2 hours, 89 % of calcium contained in the red mud was removed. For selective removal of solid silica, the residue was treated with concentrated HCl (3.0 M, l/s 20 mL/g) at 95 $°C$, resulting in dissolution of iron and aluminium content with up to 90 % efficiency. After Fe^{3+} and Al^{3+} precipitation, they were characterised by FT-IR, BET, EDS, XRD, SEM and TEM monographs, confirming the formation of nanoscale alpha hematite (α-Fe_2O_3) and mesoporous gamma-aluminium oxide (γ-Al_2O_3). Consequently, inexpensive red mud was converted into very valuable nanoscale metal oxides using simple, sustainable techniques and cheap reagents. Moreover, this method generates the least amount of waste in the leaching process and all reagents can be recycled for further use, making this method promising.

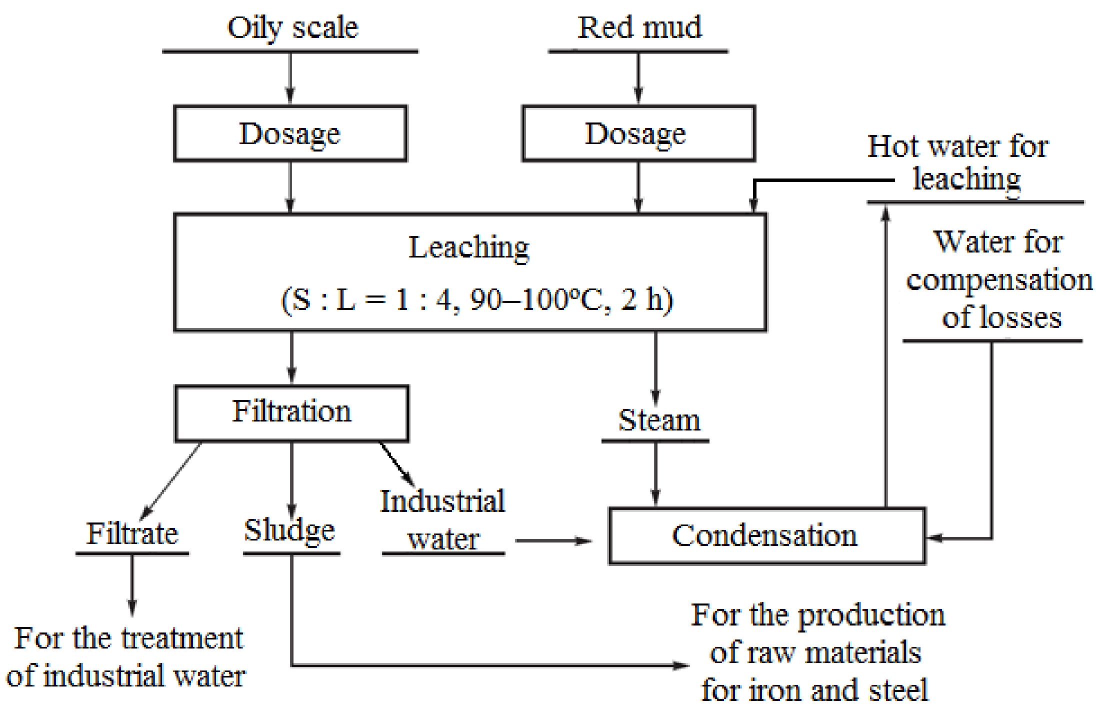

Figure 7. Technological scheme of joint processing of red mud and oily rolling scale.

The parameters of the process of carbothermal reduction of charge containing red mud and charcoal during microwave treatment have been scientifically substantiated [21]. The obtained results of experimental studies allow us to conclude about the intensifying effect of microwave heating on phase transitions from hematite to reduced iron, while providing the coarseness and uniformity of iron grains in the volume of samples is much greater than that of agglomerates obtained by conventional technology of reduction at the same temperature. The new approach to red mud processing under the influence of microwave heating creates prerequisites for creation of red mud processing technology for obtaining high-strength pelletised iron ore products with reduced iron content up to 85 %, which can become an alternative charge material for ferrous metallurgy.

4. Conclusions

Red mud is an unavoidable by-product of the Bayer aluminium production process. Due to the growth of aluminium production, the annual production of red mud in the world is continuously increasing, reaching 160 million tonnes in 2023.

Due to the lack of effective technology for processing red mud, its unclaimed mass is stored in special storages, which occupy large areas of the earth's surface, taking them out of economic use. World reserves of red mud amount to about 4 billion tonnes.

Due to its large production volume, excellent dispersibility and high alkalinity, red mud is capable of damaging the environment by polluting soil, water and atmosphere, threatening to destroy the sludge storage dam, causing an ecological disaster.

At the same time, due to the presence in the sludge of a significant proportion of iron, aluminium, titanium, as well as alloying and rare-earth metals, it should be considered as complex ore technogenic raw materials.

The optimal technology of sludge dewatering is based on the use of filter presses. This allows organizing its dry storage in a closed warehouse, which provides a reduction of the occupied space and safer storage conditions compared to sludge storages.

The most common way to regenerate alkali in the Bayer process is by adding lime to the slurry before or after the washing system, which allows 70 to 80 per cent of the alkali to be released.

Thermal methods of red mud treatment, which are carried out in drum or cyclone furnaces, in many cases are combined with physical-chemical or chemical processes of extraction of valuable components from the sludge.

Typical pyrometallurgical methods of red mud processing are three-stage waste-free processes, including production of carbon-containing pellets, their reduction roasting and smelting of reduced pellets in an electric arc furnace to produce metal and desulphurising flux.

A hydrometallurgical process for the extraction of alumina and sodium oxide from red mud allowing increasing the scale of integrated sludge recycling is used in the calcification-carbonisation method, which results in a new material structure based on $CaSiO_3$ and $CaCO_3$.

As a result of technological modeling, technological closed water intake schemes and apparatus schemes for hydrometallurgical sludge processing were developed.

Co-leaching of red mud and oily rolled scale is proposed.

The technology of step-by-step leaching of the main valuable components of red mud – iron and aluminium oxides – with the use of hydrochloric acid is proposed, which allows obtaining nanosized alpha-hematite (α-Fe_2O_3) and mesoporous gamma-aluminium oxide (γ-Al_2O_3). The advantage of this method of obtaining valuable nanoscale metal oxides is the use of simple, sustainable technologies and cheap reagents, as well as the generation of minimal waste in the leaching process.

Known proposals for the use of red mud in construction (production of cement, bricks, ceramics, fire-resistant concrete, glass fibre, for strengthening soils in the construction of roadbeds), in obtaining coagulant for energy generation and wastewater treatment, as the main component of complex binder for laying mine workings, complex raw materials for the extraction of rare earth, rare and radioactive metals.

The best prospect for large-scale industrial implementation is a complex project of waste-free processing of red mud, which provides for the first stage of pyrometallurgical extraction of thermodynamically recoverable metals, and the second stage – hydrometallurgical extraction of the remaining metals from the slag, with the subsequent direction of the final solid materials in the construction industry.

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Application of geoinformation systems in the development of the city's intelligent transport network

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Application of geoinformation systems in the development of the city's intelligent transport network

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Abstract. The purpose of the research in this article is to reveal modern approaches in the development of the intelligent transport city's networks, as a component of the social infrastructure of the modern city. The research carried out by the authors in this direction is relevant in the field regarding the improvement and attractiveness of a modern, digital city. In particular, the authors in the article examine the so-called "sleeping" districts with multi-story buildings. The authors suggest the creation of a high-speed bus transportation system to improve the services provided by public transport. The article uses the ArcGIS geoinformation system and built a geodatabase. These two components together allow you to visualize results for a visual presentation of information and qualitative analysis. The authors use such proprietary developments in the article that it is possible to model various variants of the transport network. The authors conducted research on the example of Kramatorsk, a city of regional importance in the Donetsk region. The article develops and proposes a sequence of stages in the development of a geodatabase and a transport network of high-speed bus transportation. The further direction of research may be related to the accounting of a large number of factors. The authors carried out the work with the help of the ArcGis geoinformation system and the developed geodatabase with the necessary layers and attribute information. The article develops a system of high-speed bus transportation in the city of Kramatorsk with promising routes. Such development will allow further improvement of the social infrastructure of other cities. The principle of preliminary modeling using the developed geodatabase used by the authors will be effective for solving issues related to social infrastructure, so it can be applied to solve similar problems in any city. Thus, the authors' intellectual analysis of geostatic models of public transport movement on the territory of the city made it possible to find zones and classify them depending on the pedestrian accessibility to stops and compare them with existing transport routes. With the help of geostatistics methods, the article transforms data from a discrete to a continuous form of representation.

1. Problem statement

Ground urban transport is one of the main elements of urban development, it provides transportation of the population, uninterrupted transportation of food, clothing, and medicines, connection of the people with hospitals, and many more functions. Became especially noticeable in large cities during the so-called "blackout" when ground urban transport was carried out

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precisely due to the clear coordination of ground transport.

In peacetime, and especially in wartime, the development of motor vehicles relates to the growth of the urban population and the service of its needs. And during emergencies, the use of motor vehicles should allow people to save time for trips due to the rational distribution of routes around the city. City public passenger transport carries a huge number of passengers every day. The stable operation of this sector of the economy provides about 85% of trips in urban and suburban areas. And during the "blackout", even 100% of the city's transportation was provided by city ground transport. Thus, ground urban transport is important in the infrastructure of a modern city.

But not all areas of large cities are sufficiently covered by a transport network of routes that could satisfy all the needs of the people. Thus, the task of developing or redistributing new land transport routes in a modern city arises. Necessary to connect distant parts of the city and the centre. That is, it is using innovative developments in the modelling of transport systems and the development of transport routes, which can provide city residents with greater informativeness and safety, as well as qualitatively increase the level of interaction of traffic participants in comparison with conventional transport systems.

2. Literature review

Currently, the technology of automated vehicles, that is, the intellectualization of the transport system, deserves the attention of researchers as one of the means of increasing the efficiency of high-speed bus systems. But there are some problems with such a solution. Such a modern intelligent transport system opens up unprecedented opportunities for solving problems of improving public [1–3]. The research suggests using cloud-based technologies to track a vehicle's presence on the road and adjust its speed. This structure proposed by the researchers is being field tested in the city of Sejeon in South Korea, where there are various traffic conditions such as bus stops, overpasses, underground tunnels, intersections, and pedestrian crossings. The qualities of the proposed system are compared with different types of control scenarios, and field test results show that the proposed system improves public service in various aspects, including driving safety, driving comfort, and energy efficiency [4].

It is also necessary to pay attention to the harmful emissions of carbon monoxide by bus engines. A paper for the Mumbai metropolitan region (India) suggests the use of several bus infrastructure modernization scenarios to reduce aggregate carbon dioxide emissions. The evaluation of the effectiveness of the scenarios is based on three levels of impact, i.e. conservative, moderate, and aggressive. The results show that the modernization of the bus infrastructure to a greater extent contributes to the reduction of emissions of harmful substances. The study emphasizes the priority development of high-speed bus transportation in urban planning [5].

The commercial appeal of high-speed buses is one of the most influential parameters. In the literature, many factors affect the speed of movement of buses between stops. Much research has been devoted to the study of commercial bus speed prediction. One study examines this problem using the example of Thessaloniki, Greece. The researchers developed models based on data from 10 lines of the bus network. The data included several characteristics such as the time the bus was on the road, passenger flow, bus stop location, bus stop infrastructure, etc. After that, the researchers determine the effect of the independent variables on the speed of the bus. The distance between bus stops is determined by the researchers as an important indicator of the model. The researchers found that a distance of more than 450 meters between two stops has a positive effect on the speed of the bus. Passenger waiting time for the vehicle was also an important parameter in the simulation. The researchers established that the increase in the number of traffic lights and turns on the section of the route negatively affects the speed of the buses. But the researchers did not predict the relationship between the total passenger flow and the speed of the buses [6].

Researchers pay great attention to the division of traffic lanes into lanes reserved for high-speed buses. That is, it is necessary to quantify the improvement of the quality of such transportation by high-speed bus, compared to transportation by ordinary buses. For this, the researchers suggest using an approach based on Global Positioning System (GPS) data. The speed of the line, obtained from GPS data, gives an idea of the spatiotemporal variability of the buses, and provides the necessary statistics. Studies show that a network of high-speed buses provides higher speeds with less variability compared to regular buses. However, increasing the speed of traffic in densely populated urban areas during peak hours is possible only if a separate traffic lane is allocated. Research also shows the usefulness of using GPS data recorded by vehicles to identify traffic hotspots in the city [7, 8].

In some publications, attention is paid to such a phenomenon of the transport network as excessive loading of vehicles. It reduces the quality of public service, shortens the social distance of bus passengers, and thus increases the rate of spread of epidemics, such as the coronavirus disease. In the post-pandemic era, one of the main tasks of municipal departments is to ensure sustainable city bus service. This will balance the convenience and safety of the trip for bus passengers, reduce passenger crowding, and smooth out the imbalance when boarding and disembarking passengers. A correctly calculated interval between stops can effectively reduce passenger flow during bus transportation. Thus, the appropriate design of the service network can help the administrative institutions of the city to minimize the spread of the virus, while guaranteeing the quality of transport services in the post-pandemic era [9].

A fairly common problem of the transport network is the grouping of buses at a bus stop. Solving this problem can lead to a shorter average waiting time for passengers, to less congestion of buses at bus stops. Improving the delay of waiting for a bus at a bus stop can be solved due to the timely notification of drivers in real-time mode [10].

3. Results

The authors chose the transport structure of the city of Kramatorsk as the object of the study. The total length of transport roads in the city is 347.7 km. Transportation in the city is provided by 22 bus routes, 3 tram, and 6 trolleybus routes. That is, all public transport is ground. A significant problem for citizens is the low level of pedestrian accessibility to public transport stops. In addition, the researchers observed duplication of transport routes in the city.

To solve existing problems, it was decided to introduce a system of high-speed bus transportation. Such a solution to the problem by the authors implies a comprehensive reform of the transport infrastructure in the city. For this, it is necessary to make a geo-informational analysis of the city's transport infrastructure, based on data on the population's accessibility to transport infrastructure facilities public transport stops [11]. This will allow researchers to identify weaknesses in the formation of the passenger transportation network that exists today. The authors developed a geodatabase in the ArcGIS software product [12–14]. As a result of the research, the authors created the following classes of spatial data:

- linear to represent the axis lines of transport routes (Buses, Trams, Trolleybuses);
- point to represent the population living in the relevant districts of the city (Naselennia);
- polygonal for representing transport stops (Stops).

To analyse the transport infrastructure of the city, vectorization of all active public transport routes and stops was performed (figure 1). Based on statistics on the population of the city of Kramatorsk as of July 1, 2021, the "Population" layer was created, considering the uneven distribution of the population depending on the type of development of the residential area of the city (high-rise buildings in new districts and one- and two-story buildings in the private sector) (figure 2).

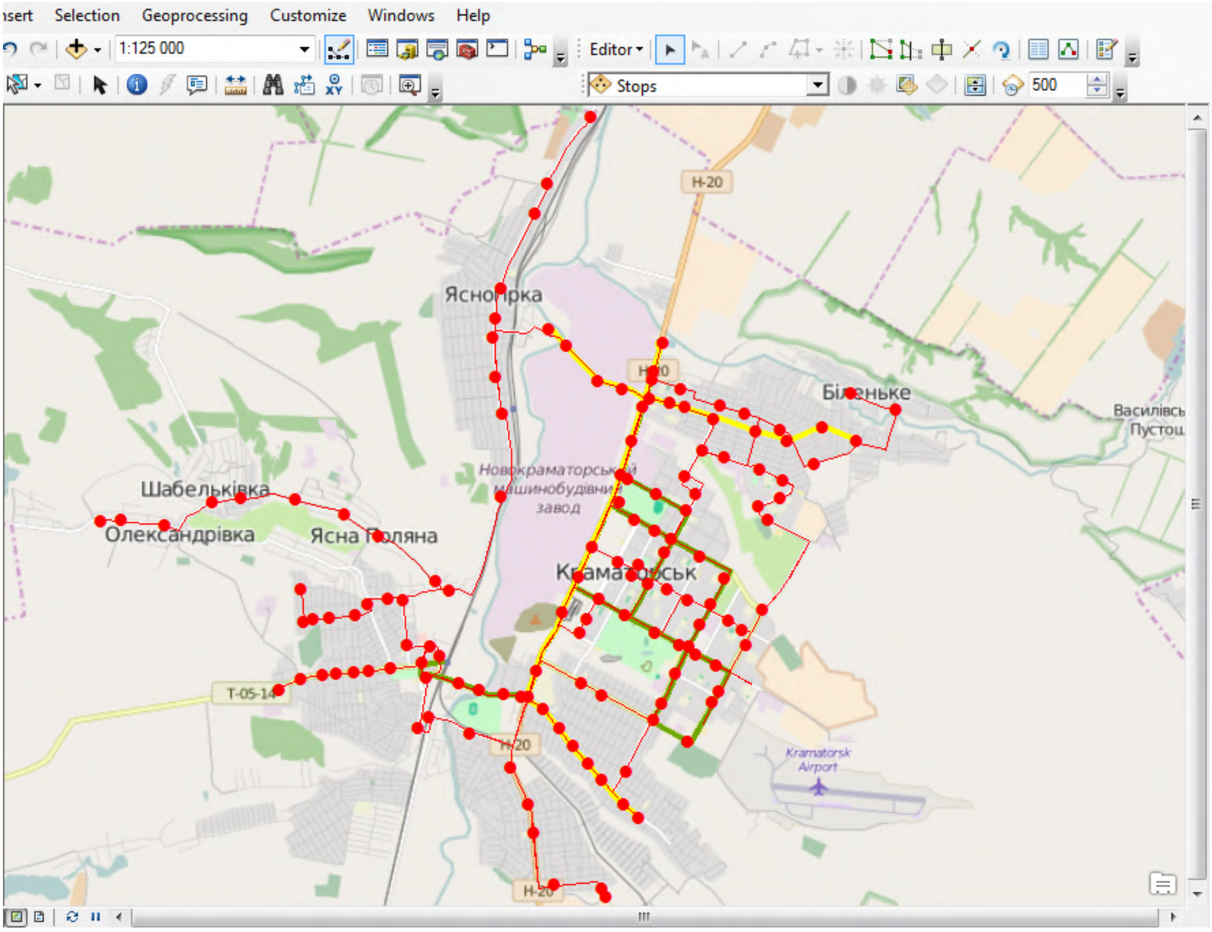

Figure 1. A network of transport routes and public transport stops.

One of the main indicators characterizing the level of public transport service is the availability of public transport stops. It is usually expressed in the range of walking approaches. Normative requirements require not to exceed a range of more than 500 m.

With the help of the ArcGis geoinformation system and the Buffer tool, the level of accessibility to public transport stops was visualized on pre-created layers (figure 3).

By analysing the attribute tables of the created geodatabase for the “Population” and “Population in the buffer” layers, information was obtained for specific areas regarding the total area of residential buildings in the area in km^2 and the area included in the 500-meter walking distance to stops. Thus, the following formula can be used to calculate the percentage of the urban population that has walking access to public transport stops:

$$D_{stops} = \frac{H_{buffer} \times 100\%}{H_{general}} \quad (1)$$

where D_{stops} is the percentage of the population that has pedestrian access to public transport stops; H_{buffer} – the area of the territory of the district (quarter), which is included in the buffer zone of pedestrian accessibility to public transport stops; $H_{general}$ – the total area of the territory of the district (quarter).

Thus, it was established that the level of pedestrian accessibility to public transport stops is extremely low:

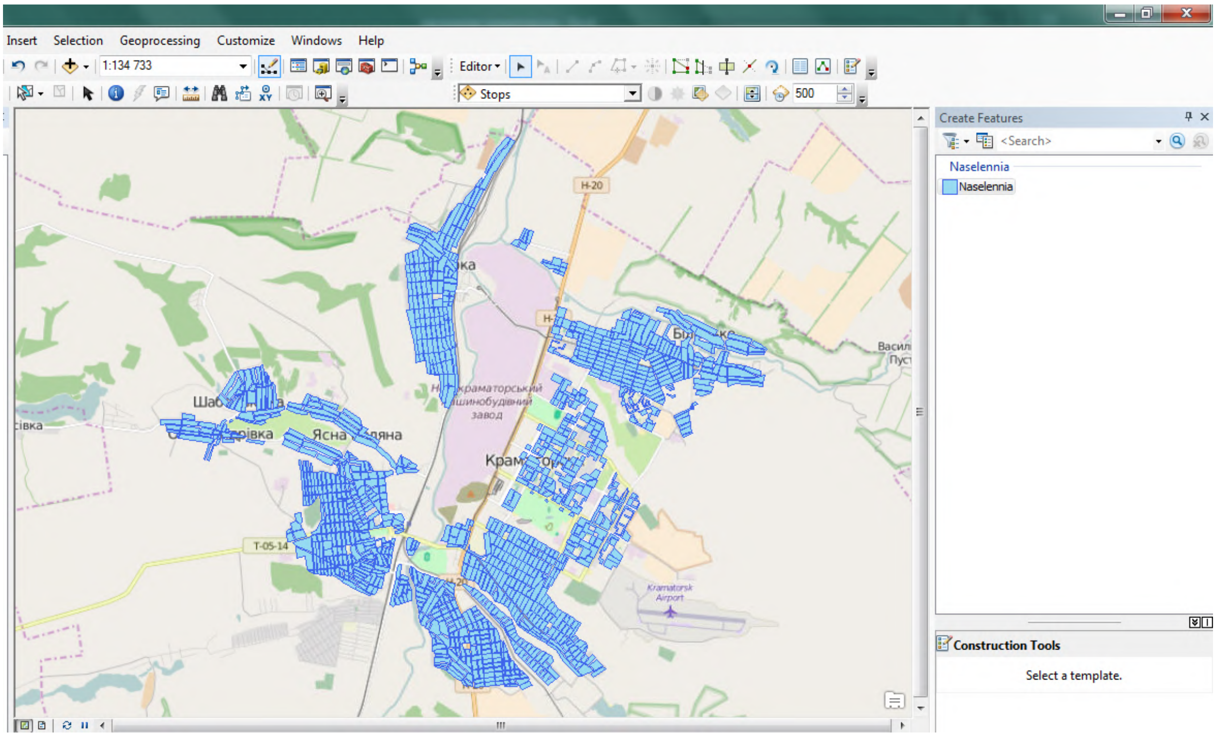

Figure 2. View of the "Naselennia" polygonal layer.

- 0-40% – 9 districts;
- 40-60% – 5 districts;
- 60-80% – 8 districts;
- 80-100% – 1 district.

As a result of the calculations, the authors determined the level of pedestrian accessibility to public transport stops in the city of Kramatorsk, which is 42.06%.

The authors determine that the introduction of a high-speed bus transportation system in the city will be able to solve such problems. Moreover, the implementation of the high-speed bus transportation system does not require additional land acquisition and the arrangement of specially allocated traffic lanes [15, 16]. The following steps must be taken to develop and implement such a modern transportation system.

The first step in the implementation of the authors' strategy should be the creation of the concept of trunk routes (figure 4). Separate traffic lanes for public transport should be organized on the main routes in the city that will connect transport hubs. To implement this task, two lanes are sufficient – one in each direction. But the right to use these lanes should be reserved exclusively for buses of the high-speed transportation system, in extreme cases, cars of the city's emergency service (police, ambulance, rescue service) may use them. To monitor the state of technical means on the route, where traffic is organized along dedicated lanes, it is mandatory to use electronic systems. Data from each bus, including from the on-board diagnostics system and from the terminal that registers tickets, are transmitted to the control room through communication means, where they are processed for further use. For priority passage through the intersection, buses must be equipped with devices that affect the traffic lights for accelerated activation of the traffic light signal, which allows movement in the direction of the bus. Traffic lights, in turn, must be equipped with receivers of such signals.

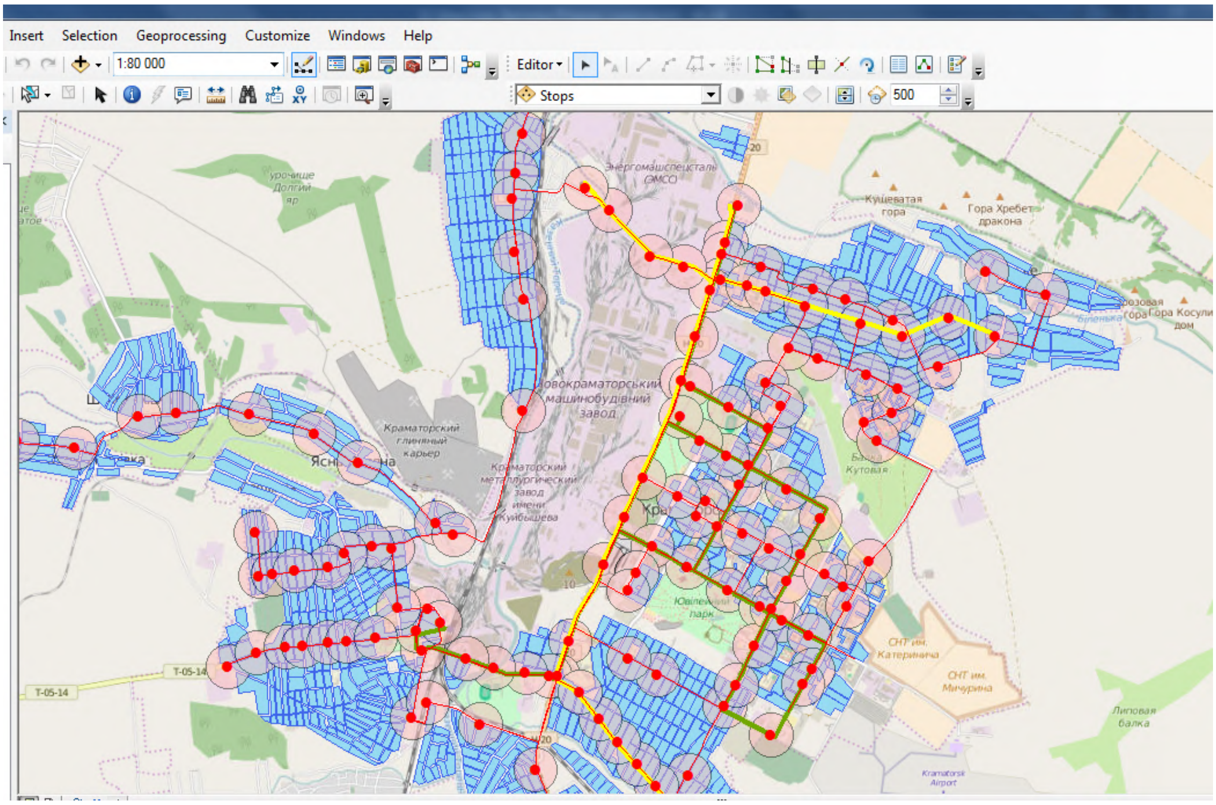

Figure 3. Buffer zones around stops along the network of transport routes.

The second step is the implementation of transport interchanges in the city. That is the introduction of a separate complex in which passengers transfer from one type of transport to another conveniently and quickly. At the same time, passenger flows during transfers are orderly, with convenient navigation. Such nodes should become the basis of the city's new transport system and will be equipped with taxi stands, bicycle parking lots, and car parking lots. To provide the passenger with data on the schedule of city transport in real-time, the deployment of a modern automated dispatching control system is required. Universal accessibility to interchange nodes will allow all people to use the advantages of public transport. To ensure fast delivery of passengers to transport hubs, the authors suggested introducing regional local routes (highlighted in green in figure 4).

The system developed in the article provides pedestrian accessibility to public transport stops by 72.53%, which is 30.74% higher than the existing one today. Such a system is basic and must still undergo several discussions with the participation of experts and community representatives in case of its practical implementation.

The use of trunk routes and transport interchanges proposed by the authors in this concept meets the modern needs of public transport in the city. This concept, proposed by the authors, is advisable to use in cities with a large population and the availability of only ground transport. The concept proposed by the authors will consider the interests of various population groups in the modern city.

4. Conclusions

The key contributions and findings of this research are:

1. A geodatabase was created with the necessary object classes to analyze indicators for

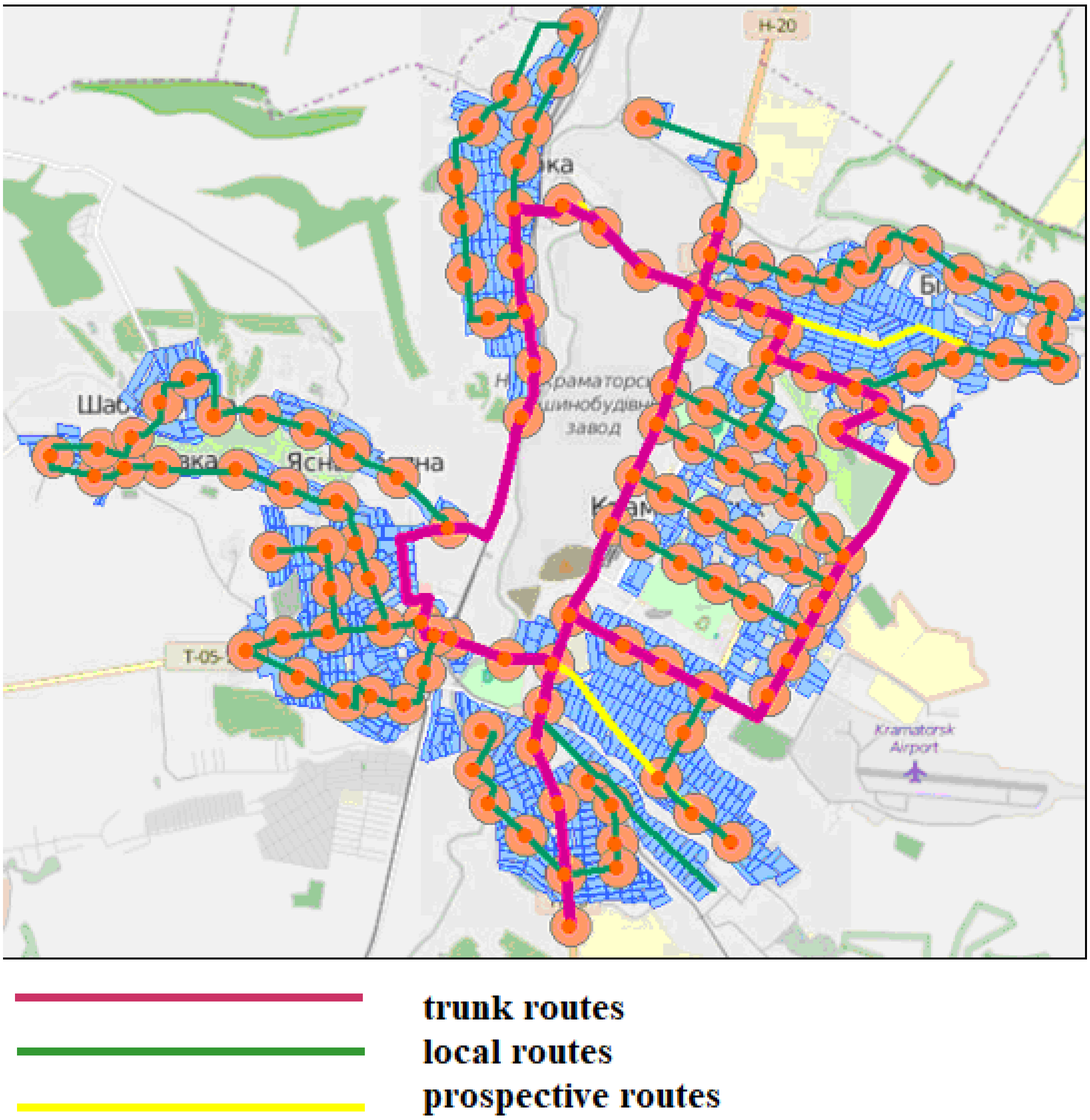

Figure 4. A system of high-speed bus transportation in Kramatorsk has been developed.

improving the city's social infrastructure, with a focus on the public transport system.

2. GIS analysis was performed to evaluate the current degree of pedestrian accessibility to public transport stops in Kramatorsk.
3. Using the ArcGIS software, an improved system of high-speed bus transportation routes was designed for the city.
4. The proposed high-speed bus system increases the population's pedestrian accessibility to public transport stops by 30.74% compared to the existing network.

The methods demonstrated in this research, leveraging geo-information technologies and GIS-based route optimization, offer significant practical value for transport planning. The results enable data-driven decision making when creating new public transport routes, and the visual outputs facilitate rapid analysis of residents' access to bus stops. While applied here to the city of Kramatorsk, the approach can be adapted to improve transport infrastructure and urban mobility in other cities facing similar challenges.

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The automated system of the trolleybus park as part of the sustainable city infrastructure

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The automated system of the trolleybus park as part of the sustainable city infrastructure

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Abstract. Trolleybuses, as an integral component of city infrastructure, play a pivotal role in sustainable urban transportation. This paper emphasizes their pivotal role in public transit, highlighting the need for advancements in monitoring and management. Recognizing the need for advancements in monitoring and management, the study advocates for the creation of a comprehensive trolleybus automated monitoring system. This system represents a critical step forward in enhancing the efficiency, reliability, and overall performance of trolleybus networks. By seamlessly integrating real-time monitoring, data analytics, and automation technologies, such systems not only facilitate proactive maintenance but also enables informed decision-making for urban planners and transit authorities. The proposed automated monitoring system aims to optimize trolleybus operations, minimize downtime, and contribute to the sustainable evolution of urban transportation. As cities worldwide strive for smarter and more efficient public transit solutions, the implementation of automated trolleybus monitoring systems emerges as a vital and strategic investment in the future of urban mobility and of sustainable infrastructure of the cities.

1. Introduction

The comfort of living in a particular city largely depends on its transportation infrastructure. The quality and expansiveness of roads, the presence of an adequate number of stops, as well as the quantity and technical condition of transportation, determine the efficiency of residents' mobility and impact their overall quality of life.

Trolleybuses play a crucial role in providing fast, environmentally friendly, and convenient transportation for city residents [1]. One of the main advantages of trolleybuses is their environmental friendliness. Trolleybuses are eco-friendly because they operate using electric power. This feature helps reduce emissions of harmful substances, contributing to the fight against environmental pollution and making trolleybuses a significant tool in urban sustainable development strategies [2]. It is also worth noting that a modern and comprehensive trolleybus system can contribute to reducing car traffic, decreasing congestion, and improving air quality in the city. A well-developed trolleybus network significantly facilitates the daily commuting of residents.

In the 21st century, automation stands out as the primary tool for enhancing any system. Automation in public transportation opens up new perspectives for improving the efficiency and reliability of transportation systems [3].

An automated trolleybus fleet management system is an integrated set of software and hardware tools designed to automate the monitoring and control of trolleybus operations. The system may include elements for monitoring the technical condition of trolleybuses, automated route planning, driver performance monitoring, as well as remote monitoring and diagnostics [4].

Unfortunately, there's currently no specialized system for monitoring trolleybuses and generating technical reports. When considering online monitoring and effectively managing sensor data, SCADA systems might seem like the obvious choice. However, they're unsuitable for our needs due to several drawbacks. SCADA systems are complex and costly to implement, lack scalability, and are heavily reliant on infrastructure. Moreover, they offer limited flexibility in sensor selection and are not equipped with technical reporting functionalities. Thus, the development of a specialized automated monitoring system for trolleybus fleets is timely and essential.

The advantages of implementing an automated trolleybus fleet management system are evident [5–8]. It allows engineers to quickly respond to technical malfunctions of trolleybuses and ensures control over electricity consumption, leading to resource savings and a reduction in operational costs.

The creation of automated systems for trolleybus fleets in cities not only helps improve the comfort and accessibility of public transportation but also contributes to the overall goal of making cities more sustainable and livable [9–11]. That is why the development of such systems is a priority today.

2. Subject area

The subject of research in this work is the system for monitoring the technical condition of the trolleybus.

The trolleybus is a complex assembly of electrical, pneumatic, electronic, and mechanical components necessary to ensure the reliable operation of this type of urban electric transport. The primary components of the trolleybus system include the electric motor, contact network, accumulator, and control system.

The generalized diagram of the trolleybus is shown in figure 1.

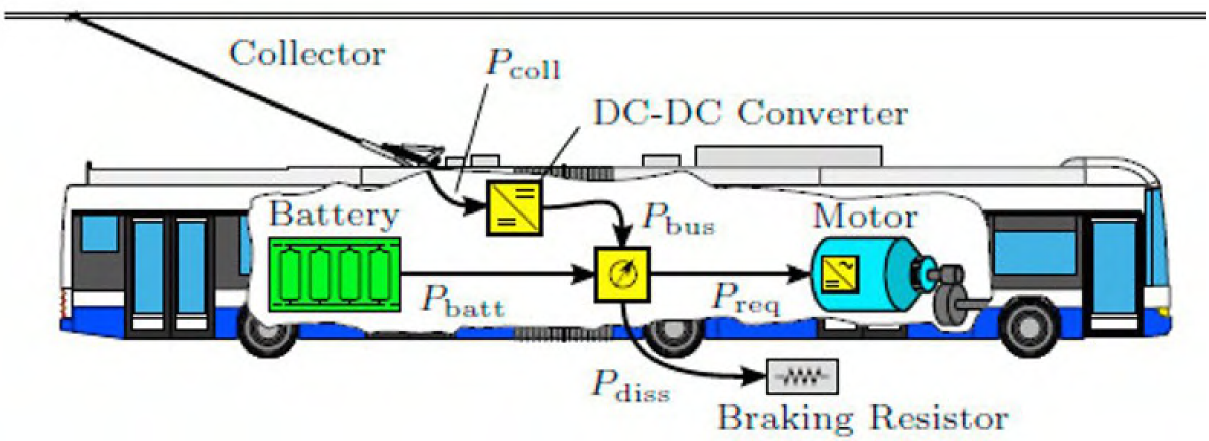

Figure 1. Trolleybus diagram.

The electric motor is the main component of the trolleybus responsible for propelling the vehicle. The electric motor operates on electrical energy supplied by the power supply system. Typically, alternating current electric motors are used [12].

The electric current to the electric motor is supplied through the contact network. The contact network is a system of wires or conductors positioned along the trolleybus route. A pantograph (collector) located on the roof of the trolleybus maintains contact with the power lines, ensuring the transfer of electrical energy from the lines to the trolleybus.

To store electrical energy for times when there are no power lines or for shorter routes outside areas without such lines, the trolleybus is equipped with an accumulator battery [13]. It consists of battery blocks, which, in turn, are made up of cells where electrical charge is stored.

The control system is responsible for coordinating the operation of the electric motor and the accumulator battery, ensuring optimal vehicle operation and efficient use of electrical energy. The control system includes controllers, sensors, and other electronic devices that regulate the current supplied to the electric motor and monitor the charge and discharge of the batteries.

Trolleybus fleet personnel must continuously monitor the technical condition of trolleybuses. Tracking such battery parameters as cell voltage, voltage drop across the block, voltage drop between all blocks, block temperature, and overall temperature differential is crucial for safety, efficiency, and the longevity of the battery system and electric motor. Cell voltage and voltage drop monitoring helps ensure an even distribution of charge among cells, enhancing battery efficiency. A high voltage drop may indicate faults in the battery that can reduce performance. Regular monitoring of block temperatures and temperature differentials helps prevent overheating, which typically leads to reduced battery life. Maintaining optimal conditions contributes to the long and efficient use of battery packs. Therefore, monitoring these specific parameters is a key element in ensuring the safety, longevity, and efficiency of battery systems in trolleybus systems.

Without the existence of an automated monitoring system in the operation of the trolleybus fleet all these parameters need to be tracked manually. To obtain data from the sensors of all trolleybuses in the fleet, each of them needs to be inspected. This process consumes a significant amount of time. Another significant drawback of such an approach is the inability to obtain data when technical expert is not near the trolleybus. Additionally, there is the risk of data loss if, for some reason, technical expert fails to record it (e.g., forgot to document the sensors data into a technical report).

3. Solution

The battery cell data collection is done primarily using the specialized voltage sensors installed on these cells. The data from the sensors are transmitted to a dedicated controller (modem), whose main function is to collect, aggregate, and structure such data. The modem can transmit data using internet protocols to other sources for data collection and processing. The collected data can be stored for further analysis and identification of prolonged or systemic issues.

The obtained from the sensors data is handled by a specialized visualization and notification system. This system enables operators to track the voltage on each cell in real-time. Additionally, the system can send notifications in case of anomalies or deviations from specified parameters.

The integration with the management system can become a crucial part of the monitoring system. This integration could enable the automatic implementation of measures in case voltage-related issues arise.

Monitoring the voltage of battery cells allows for maintaining the electric motor in an optimal operating mode, ensuring reliable and safe operation of the vehicle.

It's worth noting that in any governmental structure, there is a need for creating and storing data in a formalized format, such as technical reports. Generating technical reports on the state of a trolleybus is an essential part of its maintenance and determining its operational condition. These reports can be used to document identified issues, plan repair work, and ensure the safety of operation. Technical reports typically include the following information: trolleybus vehicle number, technical inspection data, information about systems and components, data from the diagnosis of electronic components, a description of identified faults and defects, a list of recommendations for routine maintenance and repair work, and the signature of the person who has prepared the technical report.

Technical reports creation helps to systematize information about the condition of the trolleybus, simplifies work planning and ensures efficient and safe operation of the trolleybus.

The automated monitoring system was created for the trolleybus fleet in the city of Dnipro as the result of commercial government order.

The generalized structure of the automated system is provided in figure 2.

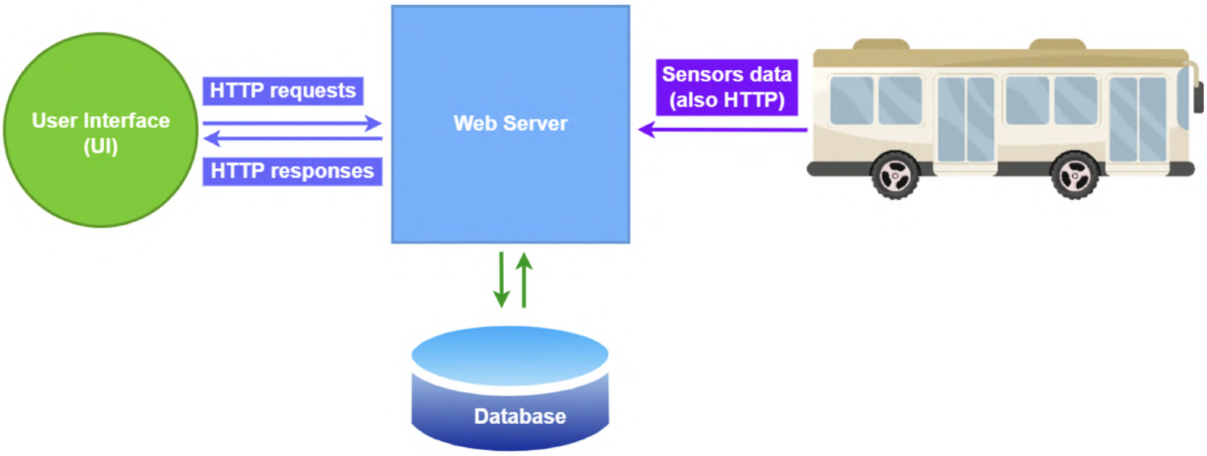

Figure 2. The monitoring system diagram.

The system consists of three main components that communicate with each other using the HTTPS protocol: web interface, web server, and a multitude of trolleybuses in the trolleybus fleet with installed controllers and sensors.

The web interface is presented as a regular website on the Internet, essentially serving as the terminal for interacting with the monitoring system. The primary advantage of such a web interface is its accessibility: trolleybus operators can access it from any device with internet connectivity (phone, tablet, desktop computer, etc.). The user interface layout has been constructed using dynamic elements, making the web interface responsive, meaning it displays equally well on screens of any size.

The web server is a key component of the monitoring system, containing all the business logic. The web server operates as a REST API service, meaning it can receive and respond to HTTP requests. The web server receives data from sensors, as well as information inputted by the user through the web interface. All incoming information is processed and structured into a format convenient for the server, and then it can be accessed by system users through the web interface. The web server stores the received information in a database.

The Teltonika TRB145 controller is installed on each trolleybus in the fleet and serves for processing and transmitting data from the trolleybus to the monitoring system. It's worth noting that the monitoring system created is entirely independent of the modem installed on the trolleybus. The data is received by the server through an HTTP request. For the server it doesn't matter which modem is used to send the data. Therefore, if the technical specialists of the trolleybus fleet decide to replace the modems on the trolleybuses, the end user of the system will not be aware of it and no changes to the system's source code will be necessary. The operators will only need to configure the new controllers for data transmission to the system server.

The development of the automated monitoring system utilized state-of-the-art web development technologies. The user interface was created using the React framework and the Typescript programming language. The web server was developed using the ASP.NET Core framework and the C# programming language. The MySQL relational database management system (RDBMS) was used for working with the database.

The main functions of the system include:

- real-time display of voltage data on accumulator batteries cells. The system provides users with the ability to view real-time data on the voltage of accumulator batteries cells in trolleybuses. This allows trolleybus operators to track the technical condition of each trolleybus and respond promptly to any anomalies;
- fault tracking. The fault tracking subsystem helps record faults and mark them as repaired. Users also have access to the history of faults for each trolleybus in the fleet. On the main page of the web interface, users can quickly identify which trolleybuses are faulty, operational, or have minor damage with each represented by different colors based on the severity of the fault;
- management of technical condition reports for trolleybuses. The system facilitates the creation, viewing, editing, and export to PDF of technical condition reports for trolleybuses covering five different types. Functionality for searching and sorting these reports is also implemented. During the creation of technical reports users can upload data from the sensors to populate relevant fields.

For the end user, the monitoring system is presented as a set of user interface screens, including:

- authentication screen;
- main dashboard screen;
- trolleybus menu screen;
- technical status screen;
- technical reports screen;
- technical report creation screen;
- technical report viewing screen;
- technical report PDF export screen;
- administrator panel.

The authentication screen (figure 3) serves as the entry point to the system. Upon successful authentication users are automatically redirected to the main screen of the system.

The main screen essentially serves as an interactive panel displaying the trolleybuses belonging to the trolleybus fleet. The icons representing trolleybuses are colored according to their current technical status, allowing operators to quickly assess the situation with the trolleybuses in the fleet. By clicking on a specific icon, the user is directed to a trolleybus menu page which contains more detailed information about that particular trolleybus (figure 4).

The trolleybus menu (figure 5) is divided into three main blocks. The first block displays information from the battery sensors collected for the current day. The second block provides a brief overview of the trolleybus's technical condition and includes a button redirecting the user to the technical status page. The third block shows a concise summary of technical reports generated during inspections, also featuring a button redirecting the user to the full page with technical reports.

Technical status screen (figure 6) presents information regarding the current technical condition of the trolleybus. Two tables are displayed on this screen: one for registering trolleybus

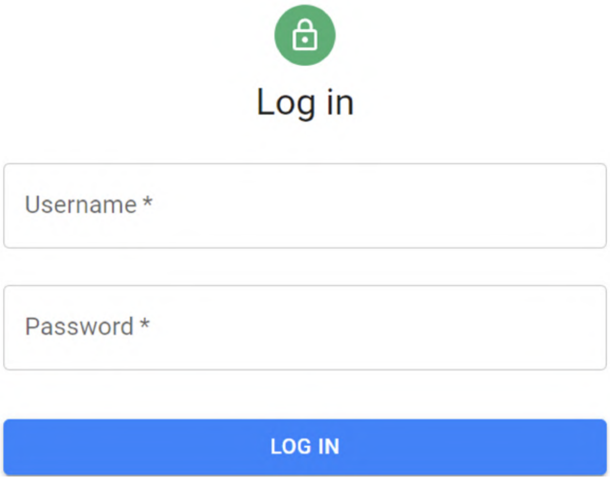

Figure 3. Authentication screen.

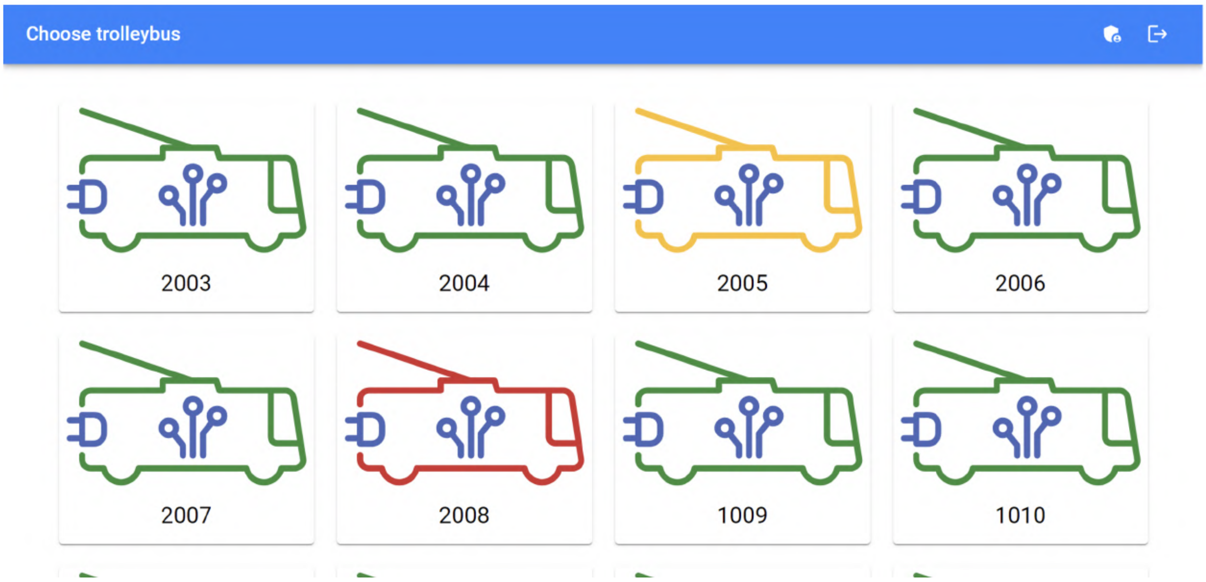

Figure 4. Main screen.

damages, and the other containing data about the trolleybus repair history. The user can manage trolleybus damages and repairs directly on this screen.

Technical reports screen (figure 7) displays a table of technical reports for the selected trolleybus. Users can sort the technical reports by creation date and type. Additionally, the screen features a button redirecting the user to the technical report creation form. If a user clicks on a specific technical report in the table, they will be redirected to a page containing the content of that particular technical report.

Technical report creation screen (figure 8) includes a technical report creation form. It's important to note that the form contains different fields depending on the selected type of technical report. At the end of the form, there is a button for creating the technical report. The form includes user input validation to ensure that the data sent to the web server is in the expected format. It is crucial to highlight that some technical reports should include information from batteries sensors and the technical report creation form allows the user to upload sensors

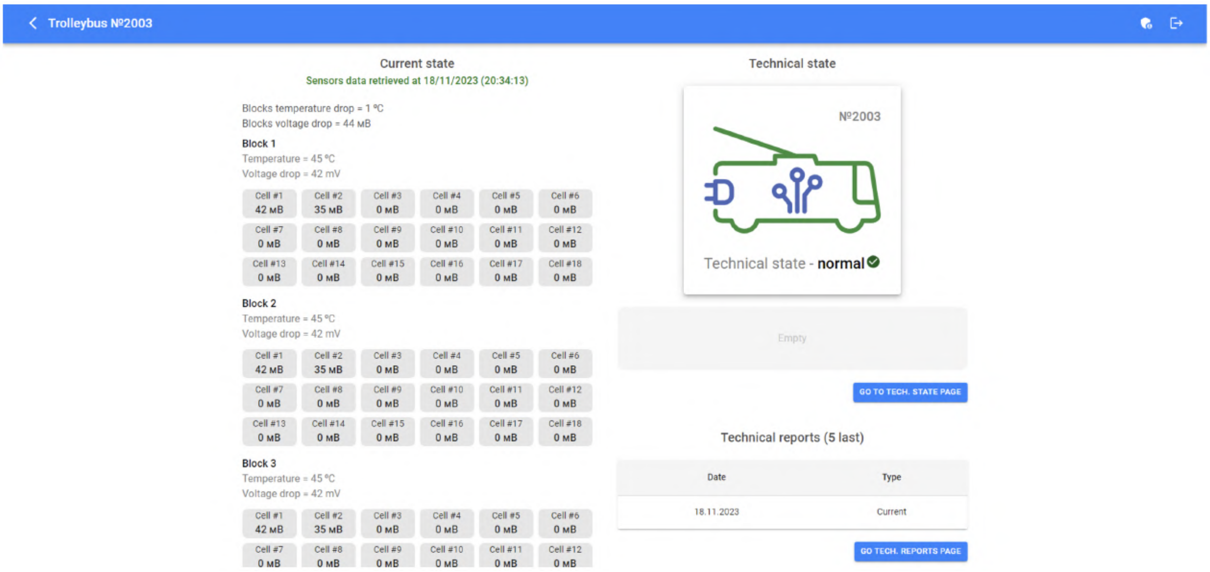

Figure 5. Trolleybus menu screen.

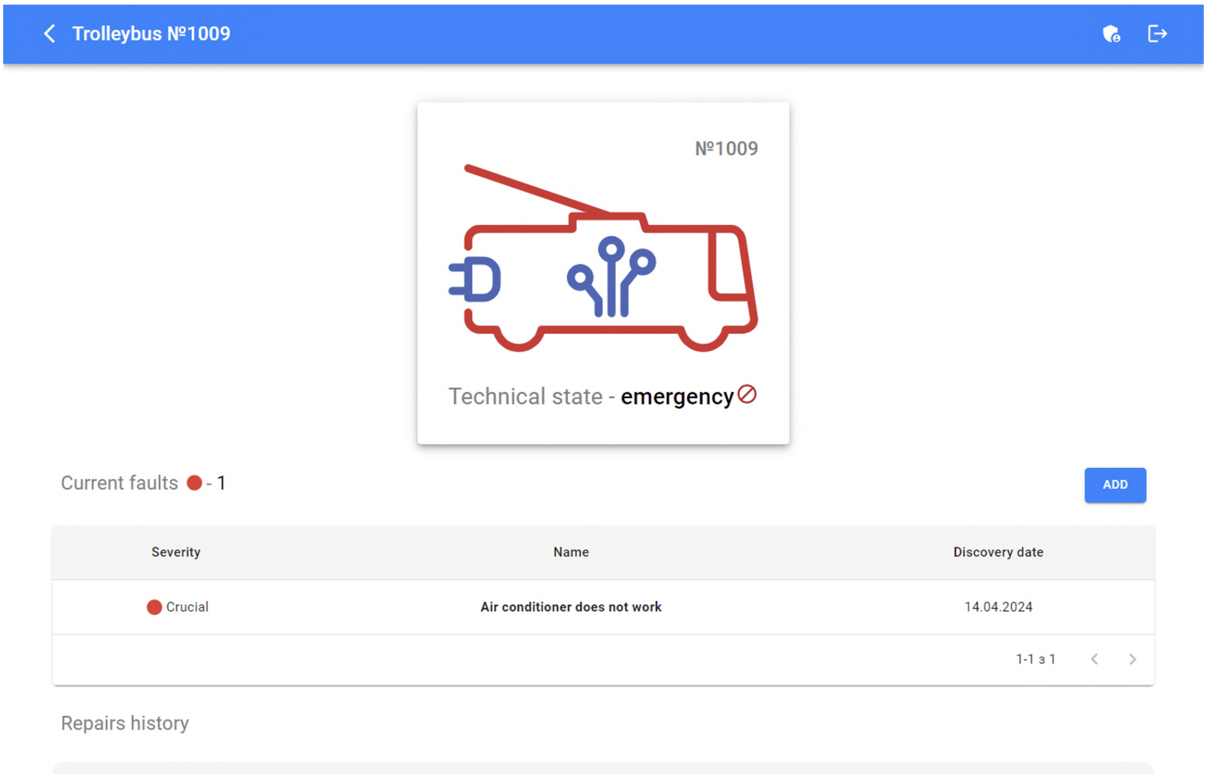

Figure 6. Technical status screen.

data to the form.

Technical report viewing screen and technical report PDF export screen are presented in figures 9 and 10.

Both screens display the created technical report. PDF export screen additionally offer the

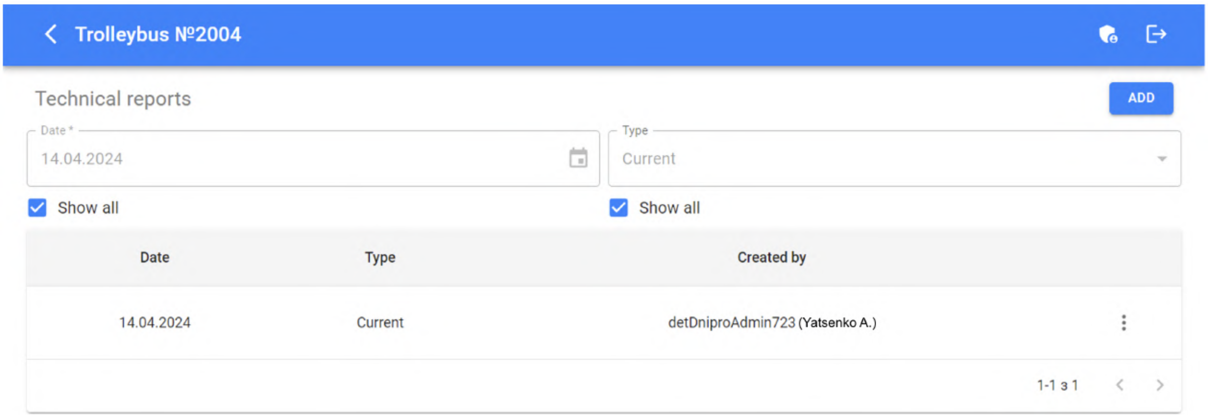

Figure 7. Technical reports screen.

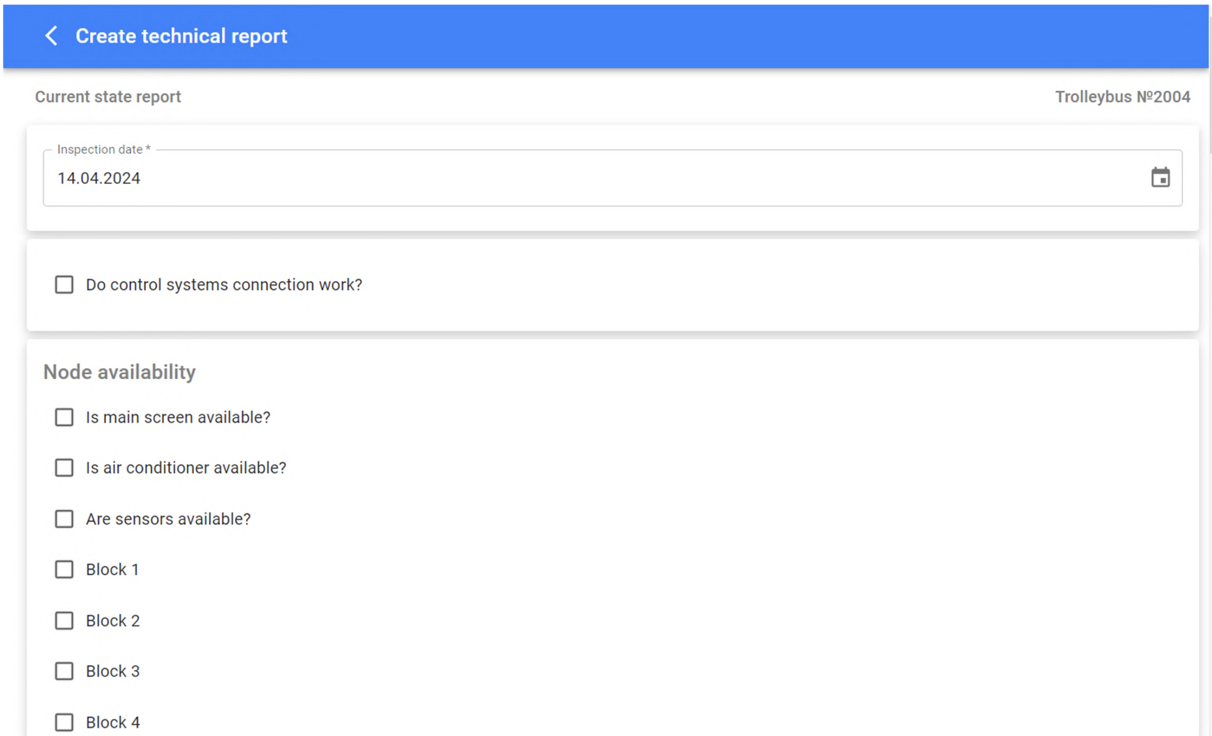

Figure 8. Technical report creation screen.

user the option to download the technical report in PDF format.

Administrator panel (figure 11) essentially serves as the control panel for the system. It contains information about system users and features functionality for managing their accounts.

There are three user roles in the system:

- Administrator (creation, deletion, and editing of user data in the system, management of technical reports, management of trolleybus malfunctions);
- Writer (ability to view and modify data);
- Reader (ability to only view data).

Significant attention was devoted to securing the developed system from external influence

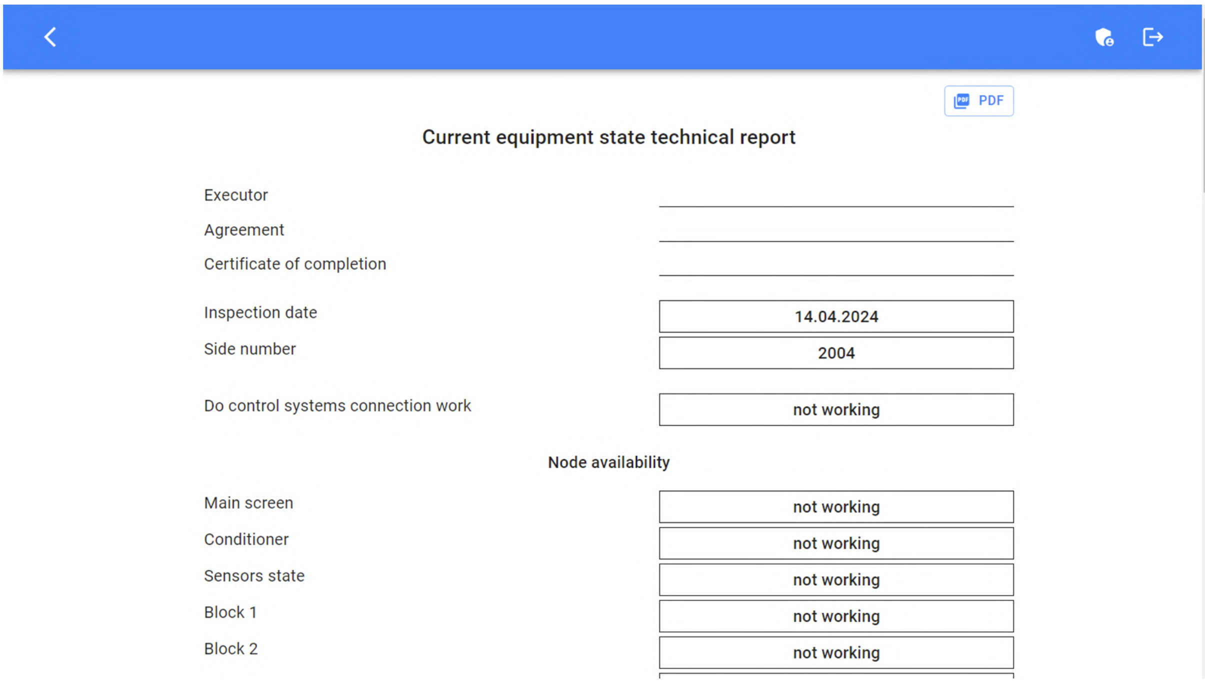

Figure 9. Technical report viewing screen.

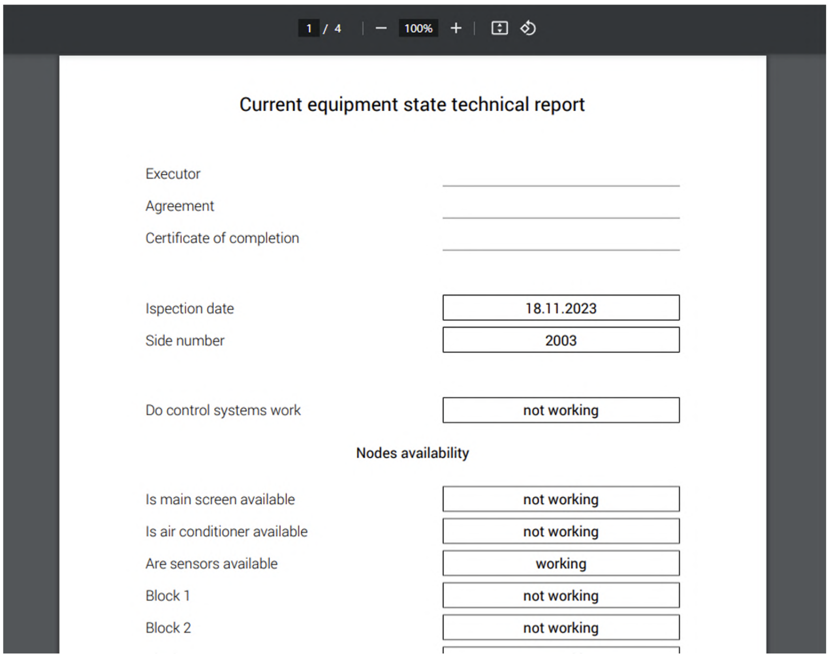

Figure 10. Technical report PDF export screen.

and unauthorized access. The authentication and authorization module, implemented using JWT tokens, allows restrict the access to the system. Access to the web interface of the system is only possible through the HTTPS protocol, ensuring encryption of all interaction traffic. The controller installed in each trolleybus in the fleet sends sensor data and the request body contains a secret token known only to the monitoring system and the controller itself, providing assurance

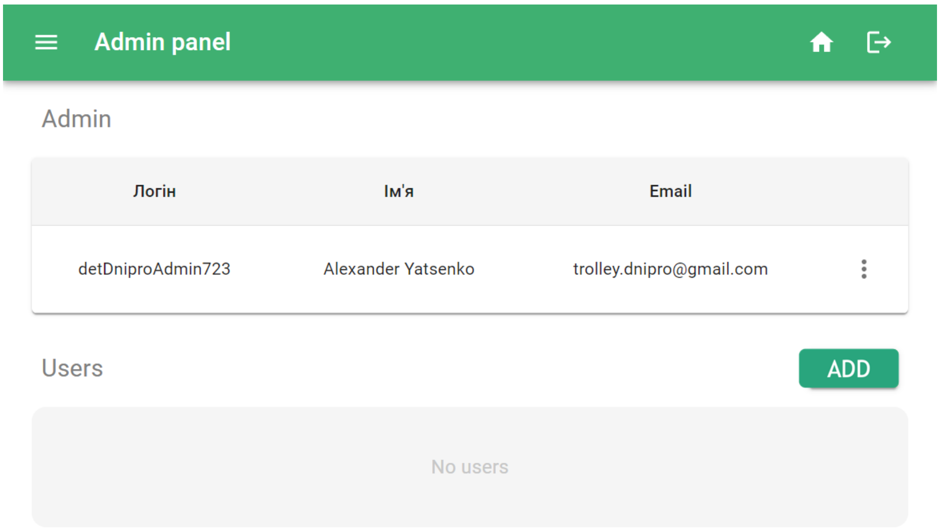

Figure 11. Administrator panel.

against data tampering. It is also worth noting that the development was carried out with an understanding of most modern web system vulnerabilities, such as SQL injections, XSS, and CSRF attacks.

The created system offers significant advantages compared to the situation where such a system is not available to the trolleybus fleet:

- rapid creation of technical status reports for each trolleybus, made possible through an intuitive interactive interface and the ability to receive real-time sensor readings (manual creation of a technical report previously took about 20 minutes, whereas with the system, it now takes 30 seconds);
- reduced number of manual errors in the automated generation of technical reports;
- efficient management of technical reports with quick access;
- export of technical reports to PDF format;
- consolidation of all technical information about each trolleybus in one centralized location;
- capability to record and manage damages to trolleybuses;
- real-time access to sensors data;
- continuous collection of sensors data, enabling future analysis;
- interactive tracking of the technical status of trolleybuses.

These advantages contribute to a streamlined and efficient process for managing and maintaining the trolleybus fleet, offering real-time insights, reducing manual effort, and improving overall data accuracy and accessibility.

4. Conclusions

The developed system represents the first step in optimizing the operation of the entire trolleybus fleet. Currently, the system includes only the functionality of monitoring the state of the battery, registering and tracking malfunctions, and generating technical reports. However, the list of functions will continue to expand as the development progresses.

Application is available on any mobile or computer device, the only requirement is Internet connection. System is designed for the Dnipro's trolleybus fleet needs (Ukraine), but can be used in any other city. The program logic is completely decoupled from the sensors used so it provides a lot of flexibility when we are talking about infrastructure needed. The application of such a system significantly enhances the quality and productivity of employees' work.

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Consideration of multifactorial geomechanical-technological factors in determining the rational parameters for site outgassing technology at the Western Donbas mines (Ukraine)

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Consideration of multifactorial geomechanical-technological factors in determining the rational parameters for site outgassing technology at the Western Donbas mines (Ukraine)

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Abstract. The paper examines a promising component for the energy sector – development of gas reserves and gas production, taking into account the peculiarities of mining-geological and mining-technical conditions of the Western Donbas deposits (Ukraine). Two components of the solution to this issue are analyzed: the texture and physical-mechanical properties of weakly metamorphosed rocks and the use of high-performance complexes, reuse of extraction drifts with resource-saving technologies for their maintenance. Based on multivariate computational experiments, schemes have been developed to determine parameters for the location of outgassing wells. Three basic methodological provisions based on the conducted analytical research performed by the finite element method have been substantiated. Calculations, which are the basis for the methodology of selecting outgassing well location parameters, have been conducted. Experimental measurements conducted at six extraction sites of two mines confirm that the outgassing coefficient according to the recommended parameters exceeds that corresponding to the existing outgassing well location schemes in mines (the range of relative increase in the outgassing coefficient is from 19 % to 123 %). In addition, a significant influence (up to 35 – 60 %) has been revealed of the coal-overlaying formation texture, the well gradient angle (20 – 30 %), and the drilling step of outgassing wells (30 – 40 %). It has been found that an increase in the longwall face advance velocity improves the gas trapping efficiency by 25 – 40 %, leading to a decrease in the methane flow into adjacent mine workings and substantiates an opportunity to accelerate the longwall face advance.

1. Introduction

Modern conditions of foreign and domestic political situation require a comprehensive and integrated development of a long-term plan for the energy component of the country's revival [1, 2].

In terms of Ukraine's energy independence, the development of gas deposits and gas production is a topical issue for the coal industry [3–5].

The conducted research, of course, proves that methane reserves in Ukrainian coal deposits are many times higher than natural gas reserves. Thus, industrial development should be directed towards the inextricable link between coal mining and gas extraction. That is, these two components have common tendencies to change [6, 7]. But there is a constraint on the operation of modern highly mechanized complexes, since the gas release process limits the rate of coal mining in terms of gas factor.

Therefore, an urgent task arises to resolve these contradictions. Scientific and practical experience has been gained in this regard [8–13]. However, a number of issues remain that relate to the specifics of the mining-geological and mining-technical conditions for mining the Western Donbas deposits (Ukraine) [14–19]. The peculiarities of mining these deposits consist in the occurrence of weakly metamorphosed rocks, that is, it is necessary to take into account in the calculations the differences in their texture and physical-mechanical properties [20–25]. On the other hand, there is a mining-technical component, which consists in the use of high-performance complexes, the repeated use of extraction drifts with resource-saving technologies for their maintenance and modern underground transport [26–31].

Thus, substantiating the site outgassing parameters for highly-stressed longwall faces in the Western Donbas mines has a significant impact on increasing coal production, which is currently the main factor in Ukraine.

Thus, the work [32] concludes that the gas release intensity from undermined coal-overlaying formation is directly related to its shear parameters. This makes it possible to reasonably select appropriate routes for site outgassing wells relative to the Western Donbas conditions (figure 1).

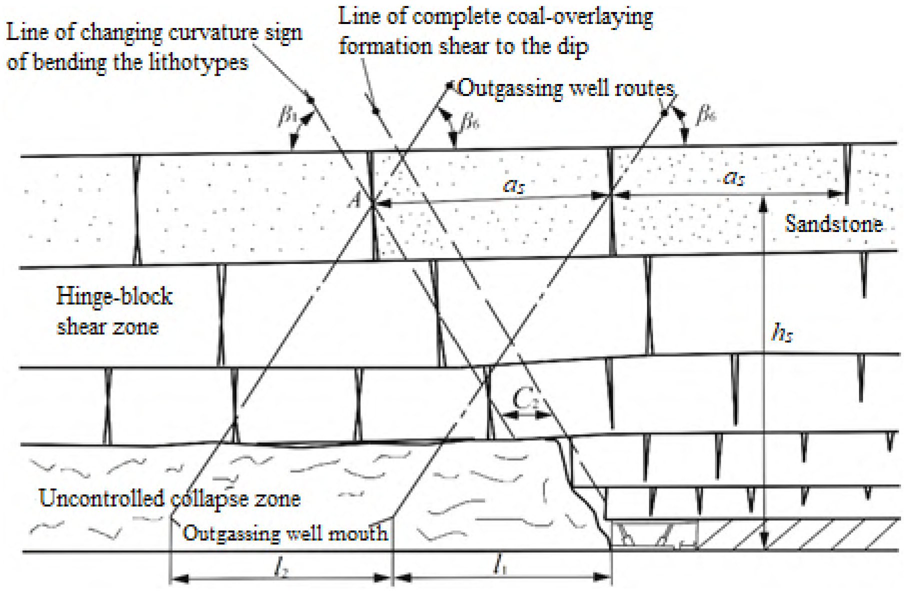

Figure 1. Scheme for determining the outgassing well location parameters to the dip of the coal seam.

Thus, a methodology has been developed for selecting the outgassing well location parameters based on the finite element method results.

The issue of scientific substantiation of the shear mechanism of the coal-overlaying formation of weakly metamorphosed rocks has been studied in the works [33, 34] for determining zones of maximum stratification and fracturing in the area of stoping operations. It is proposed to consider the shear mechanism in a spatial setting [32]. The next research step is modeling of the adjacent mass using the finite element method (FEM) [35–39] to determine the parameters of the zones of maximum stratification and fracturing. The computational model includes: a part of the rock mass ahead the longwall face and on the side of the virgin coal stratum, the mined-out space behind the longwall face, an extraction drift and the longwall face itself with a simulator of powered support. During the calculations, the texture of the coal-overlaying formation and generalized (throughout the main roof height) mechanical properties of its lithotypes, as well as the depth of the longwall face location, are changed.

Based on the conducted multivariate computational experiments, the dependences of changes in the coordinates of zones of maximum stratification and fracturing under fluctuations of the main geomechanical factors have been obtained. Regression equations have also been obtained to determine the gradient angle of the line of changing curvature sign of the main roof rock layers bending behind the longwall face and the distance of the maximum bending of the rock layers in the frontal bearing pressure zone ahead the longwall face. The methods of correlation-dispersion analysis are used to determine the dependences [40–43].

The second research component using a computational experiment is to determine the influence of the stoping face advance velocity.

2. Methodology for selecting the outgassing well location parameters based on the finite element method results

The methodology is formed based on the results of the analysis of stress-strain-state (SSS) calculations of the coal-bearing mass surrounding the longwall face end zone; these studies are performed by conducting a series of computational experiments based on the FEM, and the recommendations and conclusions provided will be adjusted based on the results of mine experiments [44–46].

The initial data for the calculation are information about the depth H of stoping operations, the texture and mechanical properties of coal-overlaying formation rocks, the planned longwall face advance velocity V_l, the layout of the equipment for drilling site outgassing wells [47–49]. The listed information is obtained from the mining-geological prediction for mining the extraction site, the longwall face passport and the passport for draining-out of gases.

Calculation of rational parameters for the location of outgassing wells has the following sequence.

1. The gradient angles of the lines of changing curvature sign of the lithotypes bending to the dip β_1 and along the strike β_3 of the coal seam are determined.
   Predominantly thin- and medium-bedded texture:
   - high mechanical properties:
     1) mudstone $\sigma_{compr} = 20 - 25$ MPa, $\sigma_{tens} = 1.5 - 2.5$ MPa, $E = (1.0 - 1.5) \cdot 10^4$ MPa;
     2) siltstone $\sigma_{compr} = 20 - 30$ MPa, $\sigma_{tens} = 2.5 - 3.0$ MPa, $E = (1.5 - 2.5) \cdot 10^4$ MPa;
     3) sandstone $\sigma_{compr} = 25 - 40$ MPa, $\sigma_{tens} = 3.0 - 4.0$ MPa, $E = (2.5 - 4.0) \cdot 10^4$ MPa.

$$\beta_1 = K_{V_l}(136.3 - 133.3H^{-0.15}); \quad (1)$$

$$\beta_3 = N_{V_l}(62.8 + 0.033H); \quad (2)$$

   - low mechanical properties

$$\beta_1 = K_{V_l}(175.8 - 242.5H^{-0.15}); \quad (3)$$

$$\beta_3 = N_{V_l}(56.6 + 0.036H). \quad (4)$$

   Predominantly thick- and medium-bedded texture:
   - high mechanical properties

$$\beta_1 = K_{V_l}(169.3 - 262.5H^{-0.18}); \quad (5)$$

$$\beta_3 = N_{V_l}(52.3 + 0.041H); \quad (6)$$

- low mechanical properties:
  1) mudstone $\sigma_{compr} = 5 - 10$ MPa, $\sigma_{tens} = 0.5 - 1.0$ MPa, $E = (0.2 - 0.3)\cdot 10^4$ MPa;
  2) siltstone $\sigma_{compr} = 8 - 15$ MPa, $\sigma_{tens} = 1.0 - 1.5$ MPa, $E = (0.4 - 0.6)\cdot 10^4$ MPa;
  3) sandstone $\sigma_{compr} = 15 - 20$ MPa, $\sigma_{tens} = 1.5 - 2.0$ MPa, $E = (0.8 - 2.0)\cdot 10^4$ MPa.

$$\beta_1 = K_{V_l}(56.9 + 0.039H); \tag{7}$$

$$\beta_3 = N_{V_l}(53.2 + 0.023H); \tag{8}$$

where

$$K_{V_l} = 1.14 - 0.028V_l; \tag{9}$$

$$N_{V_l} = 1.31 - 0.062V_l. \tag{10}$$

In equations (1) – (8), the depth H is substituted in meters, and the angles β_1 and β_3 are calculated in degrees; in equations (9) and (10), the longwall face advance velocity V_l is measured in m/day.
In the case of mining-geological conditions of averaged texture or averaged mechanical properties of the coal-overlaying formation lithotypes, the averaged value between the two limit calculations is also taken.

2. The distance value a_s of the maximum bending of sandstones in the bottom hole zone is calculated, which is also equal to the sandstone block length in the hinged-block displacement zone.
   With a height of sandstone occurrence (from the coal seam bottom) of $h_s \geq 12 - 15$ m and its thickness of $m_s \leq 2 - 3$ m:
   - for conditions of high mechanical properties

$$a_s = c_{Vl}\left[3.2 + 0.27(\tfrac{H}{100})^{2.06}\right] \tag{11}$$

   - for conditions of low mechanical properties

$$a_s = c_{Vl}\left[5.6 + 0.54(\tfrac{H}{100})^{1.92}\right] \tag{12}$$

   With a height of sandstone occurrence of $h_s \leq 10$ m and its thickness of $m_s \geq 6 - 8$ m:
   - for conditions of high mechanical properties

$$a_s = c_{Vl}\left[1.5 + 0.25(\tfrac{H}{100})^{1.77}\right] \tag{13}$$

   - for conditions of low mechanical properties

$$a_s = c_{Vl}\left[4.2 + 0.43(\tfrac{H}{100})^{1.45}\right] \tag{14}$$

   where $c_{Vl} = 1.22 - 0.044V_l$.
   In equations (11) – (14), the value a_s is calculated in meters.
3. The outgassing well route gradient angle β_4 along the strike of the coal seam is determined from

$$\beta_4 = \arctan\frac{h_s}{h_s\cot\beta_3 + C_1 + W_{pr} + W_{eq}} \tag{15}$$

   where h_s – the height of sandstone occurrence from the coal seam bottom; C_1 – the distance between the line of complete coal-overlaying formation shear and the line of changing curvature sign of its lithotypes bending along the strike of the coal seam; typically $C_1 = 2.0 - 3.0$ m; W_{pr} – the width of the extraction drift protection system; it is determined by the passport for mining the extraction site; typically $W_{pr} = 0.8 - 1.5$ m for the Western Donbas conditions; W_{eq} – the distance of the drilling equipment location from the drift working wall.

4. The outgassing well turning angle β_5 in the direction to the coal seam rise is determined from
$$\beta_5 = \arctan \frac{C_1 + W_{pr} + W_{eq}}{h_s \cot \beta_1 + C_2 + L_{eq}} \tag{16}$$
where C_2 – the distance between the line of complete coal-overlaying formation shear and the line of changing curvature sign of its lithotypes bending to the dip of the coal seam; typically $C_2 = 2.0 - 3.0$ m for the Western Donbas conditions; L_{eq} – the distance of the drilling equipment location from the well mouth is determined according to the passport for draining-out of gases at the extraction site.
5. The outgassing well gradient angle β_6 to the coal seam stratification plane is determined from
$$\beta_6 = \arctan \frac{h_s \sin \beta_5}{C_1 + W_{pr} + W_{eq}} \tag{17}$$
6. The distance of the first well from the fence of the powered support sections L_1 and the distance L_2 between the mouths of the next wells are calculated from
$$L_1 = h_s \cot \beta_1 + C_2; \tag{18}$$
$$L_2 = a_s; \tag{19}$$
7. The well length L_w is determined by the formula
$$L_w = \frac{H_m}{\sin \beta_6} + \Delta_{ov}; \tag{20}$$
where H_m – height (from the coal seam bottom) of occurrence of methane-saturated lithotypes in the coal seam main roof; it is determined according to the mining-geological prediction for the extraction site; Δ_{ov} – well overdrill length; typically $\Delta_{ov} = 2.0 - 3.0$ m.

Thus, the developed methodology makes it possible to substantiate the appropriate parameters for site outgassing well routes based on determining the patterns of influence of geomechanical-technological parameters on the coal-overlaying formation shear indices in the Western Donbas conditions.

The methodology for determining the appropriate coordinates for drilling outgassing wells is based on the conditions, criteria and a set of obtained dependences, some of which will undergo experimental testing, discussed in the next section.

3. Mine research on the relationship between site outgassing efficiency and geomechanical-technological parameters of high-velocity mining of coal seams

3.1. Research methods

Mine research has three objectives. Firstly, it is aimed to test the objectivity and reliability of the results of analytical developments and methodological provisions regarding for calculating rational site outgassing parameters, which ultimately makes it possible to increase the productivity of stoping operations. Secondly, based on the results of mine tests, it is possible to make some adjustments to the site outgassing technology parameters towards their optimal values. Thirdly, a real basis is formed for substantiating the range of expedient stoping face advance velocities according to the "gas factor", and within this recommended range of V_l it will be necessary to improve coal mining technology operations in the Western Donbas conditions.

The principle of optimizing the site outgassing technology parameters is to experimentally determine such its values at which maximum methane trapping from coal-overlaying formation rocks will be achieved. Then the gas entry into the longwall face working space and the extraction

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drifts will be minimal and, accordingly, it is possible to increase their advance velocity, which is identical to an increase in the coal-mining productivity.

The number of experimentally studied variable parameters can be reduced and the necessary information about the patterns of gas release and outgassing processes can be obtained, which are criterion factors for choosing rational parameters for the site outgassing technology in the Western Donbas mines.

3.2. Algorithm for conducting mine experiments

General methodological provisions have been implemented in the developed algorithm for conducting mine experiments, which consists of the following stages.

The first stage is testing the reliability and degree of influence of geomechanical factors, which is conducted analytically by determining a number of patterns when modeling in the FEM.

A criterion has been proposed that can be called “relative site outgassing”, which determines the level of methane gas trapping in relation to the entire volume of methane released at the extraction site. There is already such a parameter in the technical documentation – the outgassing coefficient K_{out}, which is measured in relative values. This parameter does not depend on the conditions of mining the coal seams, and it is widely used in the practice of conducting mining operations and makes it possible to compare the efficiency of selected outgassing parameters for different extraction sites. But it is still necessary to specify which parameter of K_{out} to choose in the network of mine workings, depending on the coordinates of its measurement. In our opinion, the most informative will be the parameters measured outside the longwall face in the extraction drifts near the main preparatory workings. Under such conditions, it is possible to assess the methane inflow and the degree of outgassing throughout the entire extraction site.

Another studied technological parameter is the stoping face advance velocity V_l. It also varies at the selected extraction sites. But at the first stage this does not matter, since by measuring gas flow rate and calculating the coefficient K_{out}, a “base” is created for further comparison with the same parameter K_{out} for other geomechanical-technological factors and parameters. The algorithm for comparison is as follows:

- the “basic” parameters K_{out} are recorded for specific geomechanical factors (longwall face location depth, texture and mechanical properties of the coal-overlaying formation rocks) and technological parameters (longwall face advance velocity V_l, outgassing well location scheme);
- using the developed methodology based on FEM modeling, rational parameters for outgassing well location schemes at all extraction sites, selected for experimental research, are determined;
- for these rational parameters, the volumes of gas release and gas trapping are measured and the outgassing coefficient K^r_{out} is calculated;
- values K_{out} and K^r_{out} are compared and the following conclusions are drawn. If the values K_{out} and K^r_{out} are approximately the same (the difference is up to several percent), and the outgassing well location parameters differ significantly from the “basic” ones, then the main conclusion can be drawn about the inappropriate use of the proposed methodology. If, with approximately the same parameters for outgassing well location schemes, we have a significant difference (10 – 15 % or more) in the values of K_{out} and K^r_{out}, then this indicates the inadequacy and unreliability of the proposed methodology. If the rational parameters for outgassing well location differ significantly from the “basic” ones, and the values of K^r_{out} are significantly higher than K_{out}, then we conclude that it is advisable to use the developed methodology.

This general conclusion is the essence of the first stage of mine research: it substantiates the feasibility of using the methodology, but does not answer the question of the degree of its reliability.

The second stage is assessing the degree of correspondence of the influence patterns of geomechanical factors, obtained analytically and experimentally in mine research. Here the main purpose is to test the reliability of the dependences obtained in previous sections during the FEM modeling of the shear processes in the coal-overlaying formation rocks behind the longwall face. At the same time, it should be noted that there is an indirect method for assessing the reliability of the analytical research results, since it is not possible to "directly" experimentally record such parameters as: gradient angles of the lines of changing curvature sign of the lithotypes bending in the coal-overlaying formation to the dip β_1 and along the strike β_3, the distance a_s (from the stoping face plane) of the zone of the maximum bending stresses acting in the rock mass.

Three main geomechanical factors (the longwall face depth, the texture and mechanical properties of the coal-overlaying formation rocks) have been identified, the influence of each of which is studied experimentally in the following way. A fairly wide range of variations in the depth H of the longwall face location is provided by studies at six extraction sites of two mines: 501, 503, 962 and 1124 longwall faces of the Heroiv Kosmosu mine, as well as 885 and 1043 longwall faces of the Zakhidno-Donbaska mine. In addition, there is a certain change in H at the extraction sites during their mining to the coal seam rise. With regard to variations in the texture and mechanical properties of the coal-overlaying formation rocks, they usually occur within a certain range at each extraction site (figure 2). And since six of them are studied at two mines, the range of variation of these geomechanical factors is quite representative (figure 3).

Thus, an experimental research into the patterns of influence of geomechanical factors on the site outgassing technology efficiency of extraction panels has been provided.

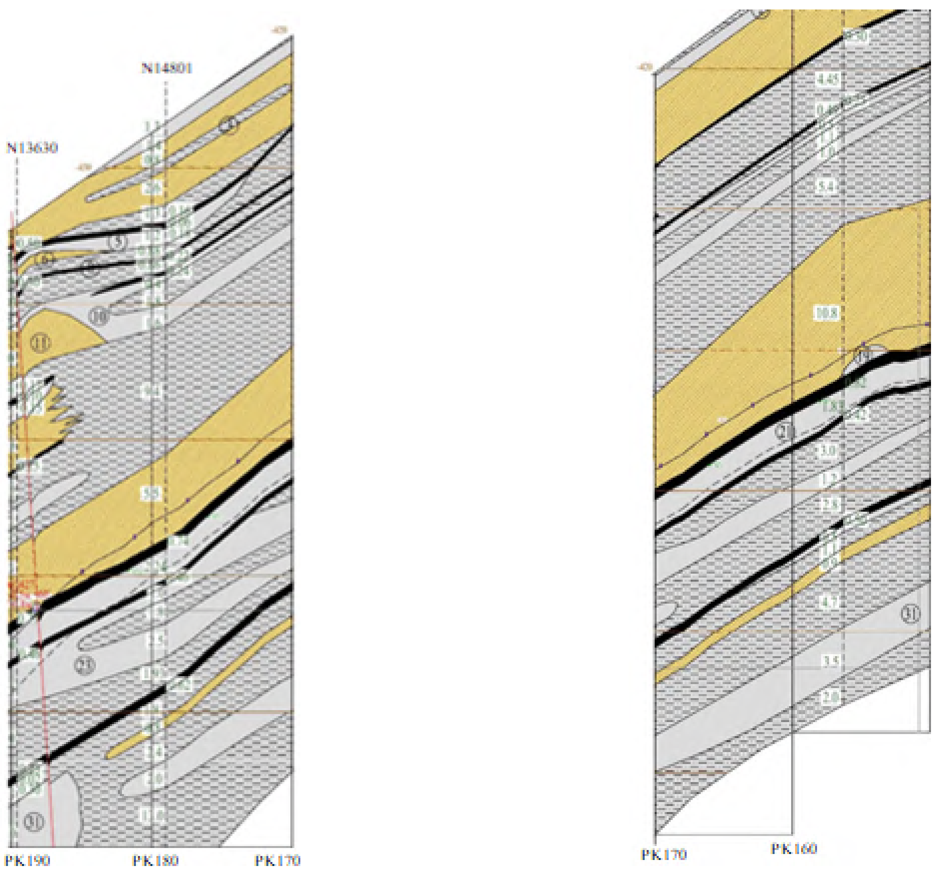
The third experimental research stage involves studying the influence of a number of technological parameters on the outgassing process efficiency, among which three main ones are: longwall face advance velocity V_l, gradient angle β_6 of outgassing wells to the coal seam stratification plane, the step l_2 of drilling wells along the extraction drift, that is the distance between the mouths of adjacent wells.

As a result, the developed methodological provisions and the algorithm for conducting mine experiments will allow to achieve the purpose set – a comprehensive assessment of the adequacy and reliability of recommendations for determining the rational parameters of site outgassing technology at the Western Donbas mines.

4. General assessment of the objectivity of recommendations on selecting the site outgassing technology parameters

According to the developed methodological provisions and a well-founded algorithm for conducting mine research, their results are presented sequentially, starting with the first stage regarding the assessment of the rationality degree of the recommendations on selecting the site outgassing technology parameters, developed on the basis of analytical research on the processes of the coal-overlaying formation shear into the mined-out space behind the longwall face using the FEM. The methodology of the first mine research stage involves the calculation of site outgassing technology parameters according to the recommended methodology, followed by a comparison of the outgassing coefficient K_{out}^r with its value K_{out} based on the available parameters, used at extraction sites according to their passport for draining-out of gases. The main purpose of this research is to assess the influence of geomechanical factors while testing recommendations in different mining-geological conditions. For this purpose, six extraction sites in two Western Donbas mines have been selected.

The mine research first stage results are shown in figure 4 in a somewhat limited form; the main reason is to provide a more informative look to the graphs $K_{out}^r(H)$ and $K_{out}(H)$ for



(a) (b)

Figure 2. Fragments of the mining-geological section along the extraction site of the 501 longwall face of the Heroiv Kosmosu mine: (a) – predominantly medium-bedded texture; (b) – predominantly thick-bedded texture.

individual extraction sites (501 and 503 longwall faces of the Heroiv Kosmosu mine, as well as 1043 longwall face of the Zakhidno-Donbaska mine).

Thus, from the comparative analysis, the main tendency is consistently observed (for different mining-geological conditions): the outgassing coefficient according to the recommended parameters K_{out}^r exceeds the corresponding value of K_{out} for the existing parameters of outgassing well location schemes. For example, for 1043 extraction site of the Zakhidno-Donbaska mine, the difference in coefficients K_{out}^r and K_{out} ranges within 0.143 – 0.280, that is 29 – 74 % in relative units. That is, if to adhere to the proposed recommendations, then it becomes possible to increase the load on the longwall face by 29 – 74 % according to the so-called “gas factor”.

Regarding two extraction sites (501 and 503 longwall faces) at the Heroiv Kosmosu mine, there is also an excess of K_{out}^r over K_{out} (figure 4), which in relative units has a significant value: 31 – 123 % for 501 extraction site; 23 – 85 % for 503 extraction site. Of course, in the provided ranges of fluctuations, the maximum values of the ratios K_{out}^r and K_{out} should be considered as unit – they do not characterize their real difference, but an increase in the outgassing coefficient by 20 – 30 % is quite possible, and this contributes to a significant increase in the extraction site productivity in terms of the “gas factor”.

At different ratios of geomechanical factors, there is a tendency for the outgassing coefficient

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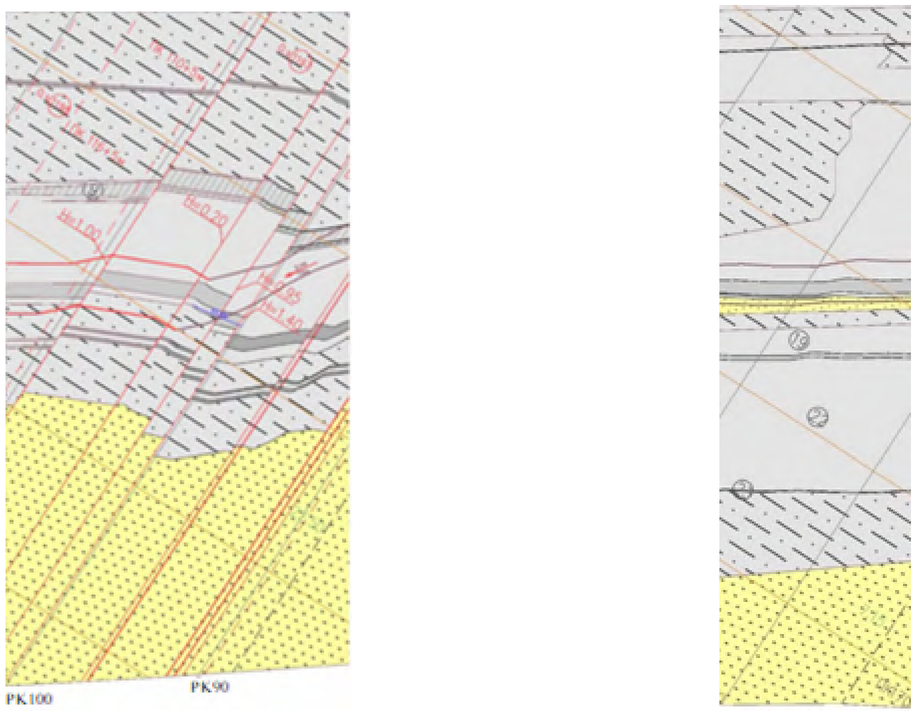

(a) (b)

Figure 3. Fragments of the mining-geological section along the extraction site of the 1043 longwall face of the Zakhidno-Donbaska mine: (a) – predominantly medium-bedded texture; (b) – predominantly thick-bedded textureе.

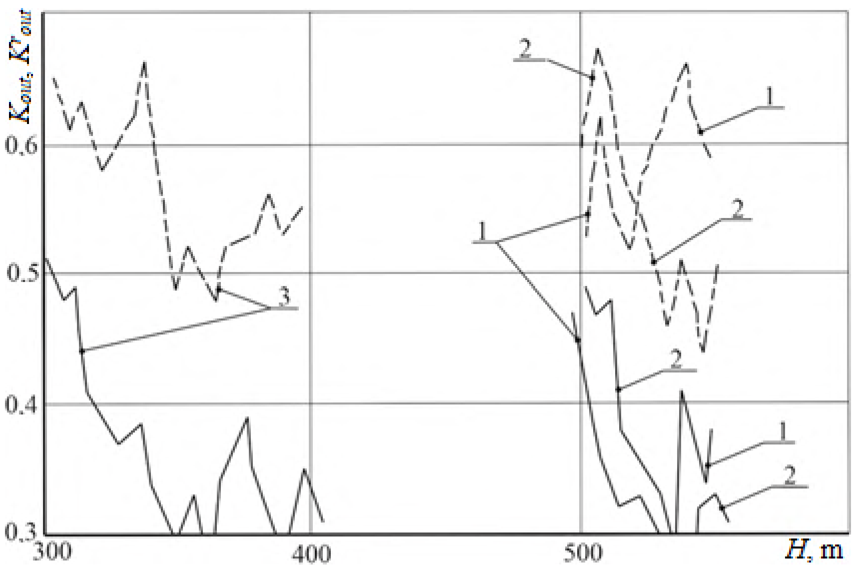

Figure 4. To a comparative analysis of existing and recommended parameters of site outgassing schemes: 501 (1) and 503 (2) longwall faces of the Heroiv Kosmosu mine and 1043 (3) longwall face of the Zakhidno-Donbaska mine.

to decrease with increasing longwall face depth H; this tendency is noted at all extraction sites, both with the existing schemes for outgassing well location, and at the majority of experimental sites with the recommended outgassing parameters.

Summarizing the results of the first experimental research stage, it is possible to confidently speak about the feasibility of subsequent, more deterministic stages of mine experiments of site outgassing technology according to the recommended parameters for the outgassing well location.

5. Influence of geomechanical factors on site outgassing parameters

The main purpose of the second research stage is to determine the tendencies in the influence of geomechanical factors (the longwall face location depth H, texture and mechanical properties of the coal-overlaying formation rocks) on the site outgassing efficiency, as well as to study the differences in its performance with the existing and recommended parameters for outgassing well location schemes.

The results of recording the gas release and gas trapping volumes, as well as the subsequent calculation of outgassing coefficients K^r_{out} and K_{out}, are graphically shown in figure 5 and figure 6.

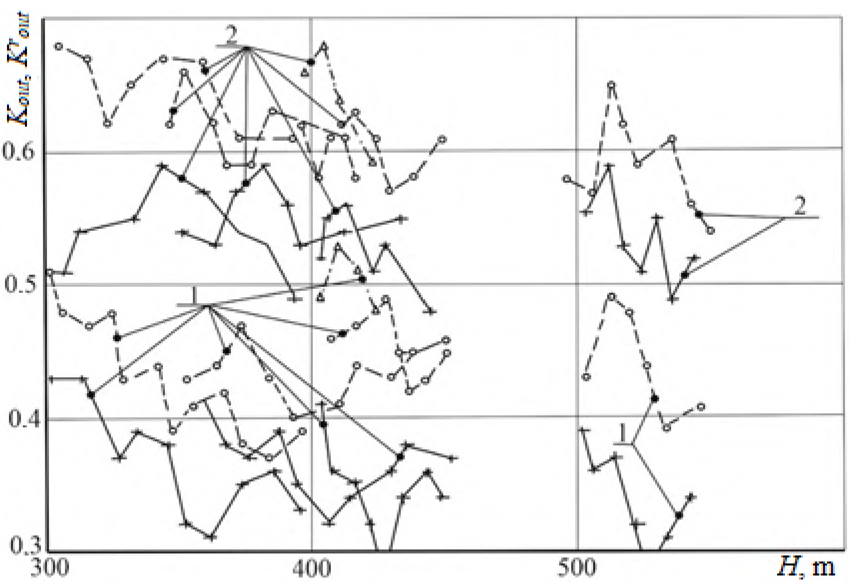

Figure 5. Patterns of texture influence on the effectiveness of existing (1) and recommended (2) site outgassing schemes: predominantly thick-bedded texture; predominantly medium-bedded texture; predominantly thin-bedded texture.

Then, study the tendencies of the influence of the coal-overlaying formation rock texture, which is divided into three groups: predominantly thin-bedded, predominantly medium-bedded, and predominantly thick-bedded. Such a division is capable of covering almost all coal mass texture types observed in the Western Donbas, and a clear identification of the lithotype thickness according to the existing classification (thin, medium and thick) is practically impossible, because it is not found in the geological mass structure. It should also be noted that the graphs in figure 5 have gaps (along the coordinate H), which separate parameters K^r_{out} and K_{out} for different extraction sites.

There is a steady tendency for outgassing coefficients to be exceeded at more stratified roof than at less stratified roof, regardless of the selected parameters for outgassing well location schemes. For example, for the 503 extraction site of the Heroiv Kosmosu mine, two types of textures are distinguished: predominantly medium-bedded texture and predominantly thick-bedded texture. When comparing the coefficients K^r_{out} and K_{out}, it is noted that for a

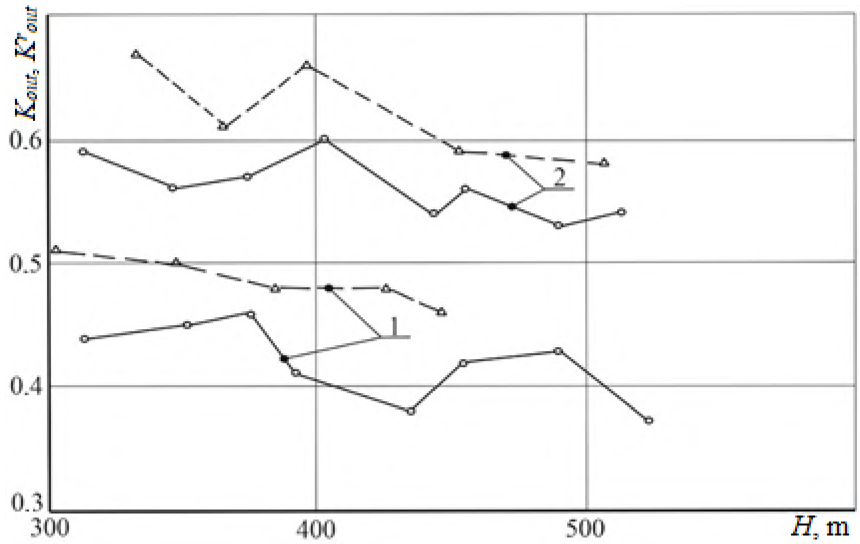

Figure 6. Patterns of influence of mechanical properties of coal-overlaying formation rocks on the effectiveness of existing (1) and recommended (2) site outgassing schemes: low and averaged mechanical properties.

predominantly medium-bedded texture the coefficient K^r_{out} is higher by 1 – 25 %, and for a predominantly thick-bedded texture the coefficient K_{out} is exceeded by 10 – 63 %. Similar tenedencies are observed for other extraction sites: 962 longwall face of the Heroiv Kosmosu mine – there is an excess of 6 – 24 % for K^r_{out} and 11 – 55 % for K_{out}; for 1043 longwall face of the Zakhidno-Donbaska mine, the corresponding ranges are equal to 14 – 37 % – K^r_{out} and 3 – 34 % – K_{out}; for 885 longwall face of the Zakhidno-Donbaska mine, the following excesses are: 2 – 19 % – K^r_{out} and 6 – 27 % – K_{out}.

The predominantly thin-bedded texture of the coal-overlaying formation rocks has been identified only in separate sections of the 962 extraction panel. When comparing predominantly thin-bedded and predominantly thick-bedded textures, an excess of the coefficient K^r_{out} by 13 – 30 % and K_{out} by 20 – 71 % has been obtained.

The main conclusion from the above results is this: the texture of coal-overlaying formation rocks has a significant influence on the outgassing efficiency, regardless of other geomechanical-technological factors; therefore, the type of texture should be taken into account when choosing parameters for site outgassing well location schemes.

Another main task of the second research stage is to determine the tendencies of influence of mechanical properties of coal-overlaying formation rocks on the site outgassing efficiency according to the criterion of comparison of coefficients K^r_{out} and K_{out} with different strength characteristics of lithotypes.

Figure 6 shows plotted graphs of the change in outgassing coefficients K^r_{out} and K_{out} for two variants of the generalized strength characteristics of coal-overlaying formation rocks (reduced and averaged) according to the depth coordinate H of the longwall face location. It should be noted here that the number of areas with approximately the same texture, but different mechanical properties, is very limited. Therefore, the influence of the mechanical properties of lithotypes can only be observed at the level of tendencies in changes in K^r_{out} and K_{out}, but this information also has some benefit in terms of the evidence base for the feasibility of using the developed recommendations.

From the experimental data analysis, the moderate influence of the generalized strength characteristics of coal-overlaying formation rocks can be clearly seen, which can be given in quantitative terms on the following examples: with the recommended parameters for site outgassing well location schemes, the outgassing coefficient K^r_{out} is higher by 5 – 17 % for predominantly reduced mechanical properties than in the case of their predominantly averaged values; relative to the existing parameters for outgassing well location schemes, the excess of K_{out} is by 4 – 24 %.

The final conclusion is as follows – despite the moderate influence of the mechanical properties of coal-overlaying formation rocks, this geomechanical factor should also be taken into account when substantiating the parameters for site outgassing technology, since the final multifactorial influence of geomechanical factors consists of the total effect of each of them. And the existence of such an influence once again confirms that the outgassing coefficient K^r_{out} according to the recommended parameters for outgassing well location schemes exceeds the existing ones by 24 – 38 % with reduced mechanical properties and by 25 – 49 % with the averaged mechanical properties of coal-overlaying formation rocks.

6. Influence of technological factors on site outgassing parameters

At the preliminary experimental research stages, a significant influence (on the site outgassing efficiency) of geomechanical factors has been revealed. However, the identified patterns together with technological factors differ from each other for different extraction panels examined in terms of fixing gas release and gas trapping with subsequent calculation of outgassing coefficients K^r_{out} and K_{out}. Now it is the turn of the third experimental research stage, the purpose of which is to determine the level of influence of the technological parameters of the site outgassing process, among which three main ones were identified earlier: the longwall face advance velocity V_l, the gradient angle β_6 (to the coal seam stratification plane) of the outgassing wells, and the step l_2 of drilling them along the extraction drift.

The results of gas release and gas trapping measurements are given in figure 7 in the form of dependency graphs of the coefficients K^r_{out} and K_{out} on the longwall face advance velocity V_l. These graphs illustrate data only for individual extraction sites. Thus, for 501 longwall face, there is an increase in outgassing coefficients with an increase in its advance velocity V_l: the outgassing coefficient K^r_{out} according to the recommended schemes for outgassing well location increases up to 34 % in the range of $5.2 \leq V_l \leq 8.7$ m/day; the outgassing coefficient K_{out} with existing technological parameters increases up to 71 % in the range of $5.1 \leq V_l \leq 8.5$ m/day. Similar tendencies have been observed for other extraction sites: 503 longwall face – up to 15 % (5.0 – 6.1 m/day) and up to 33 % (4.9 – 6.1 m/day), respectively; 962 longwall face – up to 47 % (5.9 – 8.2 m/day) and up to 36 % (6.0 – 7.6 m/day); 1043 longwall face – up to 18 % (4.7 – 7.1 m/day) and up to 24 % (4.8 – 6.9 m/day).

The main conclusion from the above data is that an increase in the longwall face advance velocity V_l (by an average of 30 – 45 %) contributes to an increase in the gas trapping efficiency by an average of 25 – 40 % under various mining-geological conditions of mining the Western Donbas coal seams. In other words, tendencies in the same direction of increasing the coal mining productivity have been identified: the growth of V_l leads to a decrease in the methane inflow into the adjacent mine workings (when using site outgassing technology), and this, in turn, substantiates the possibility of accelerating the longwall face advance. This main conclusion is confirmed by another experimentally determined fact – with the recommended schemes for outgassing well location, the outgassing coefficient increases (relative to that with existing parameters) in the ranges of 9 – 46 % (501 longwall face), 20 – 56 % (503 longwall face), 13 – 27 % (962 longwall face), 10 – 28 % (1043 longwall face). Thus, there is a potential to increase the coal mining productivity by "gas factor", and it may become secondary to other structural and technological factors in the operation of highly-stressed longwall faces.

The next technological factor influencing the outgassing efficiency (based on the FEM modeling results) is positioned as the gradient angle β_6 to the coal seam stratification plane

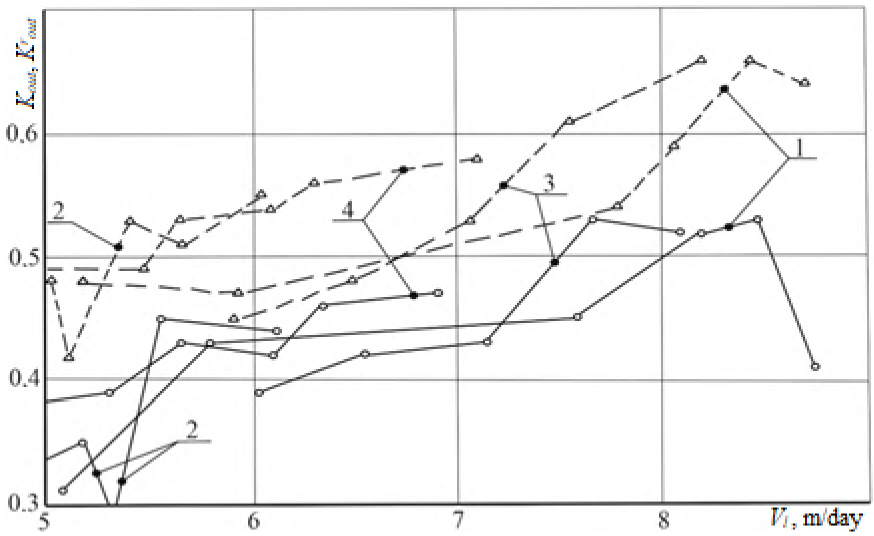

Figure 7. Patterns of influence of the longwall face advance velocity V_l on the effectiveness of existing and recommended parameters of site outgassing schemes: 501 (1), 503 (2) and 962 (3) longwall faces of the Heroiv Kosmosu mine; 1043 (4) longwall face of the Zakhidno-Donbaska mine.

of the outgassing wells. For each extraction site (from the list of those studied), three values of K_{out} have been determined at different gradient angles β_6 in the variation range of $43^{\text{o}} \leq \beta_6 \leq 68^{\text{o}}$.

The research results in the form of dependency graphs K_{out} (β_6) are shown in figure 8, from which it is clear that the tendencies of the angle β_6 influence are somewhat ambiguous. For example, for extraction sites No. 501, 503 and 962 of the Heroiv Kosmosu mine, there is an increase in value of K_{out} with increasing outgassing well gradient angle β_6, and this increase occurs over the entire range of β_6 changes. But the gradient of the increase in K_{out} decreases with growth of β_6, which indicates an approach to a certain maximum, that is, in our research, to a rational value of β_6. The existence of such a value is indicated by the dependency graphs K_{out} (β_6) for other extraction sites: No. 1124 of the Heroiv Kosmosu mine and No. 885 and No.1043 of the Zakhidno-Donbaska mine. The maximum of K_{out} is clearly observed here, but with the only three experimental points on the graphs, it is impossible to determine the reliability of the rational values of outgassing well gradient angle β_6. What can be stated for sure is the significance of β_6 influence; the difference between K_{out} values for different β_6 values is: 36 % for 501 longwall face, 29 % for 503 longwall face, 17 % for 962 longwall face, 56 % for 1124 longwall face of the Heroiv Kosmosu mine and 20 % for 885 longwall face and 24 % for 1043 longwall face of the Zakhidno-Donbaska mine.

The outgassing coefficient K_{out} measurement and calculation results are shown graphically in figure 9 for each studied extraction site separately. As expected, there is an increase in K_{out} with a decrease in l_2 at all extraction sites: by 26 % for 501 longwall face, by 47 % for 503 longwall face, by 26 % for 962 longwall face and by 40 % for 1124 longwall face of the Heroiv Kosmosu mine; by 51 % for 885 longwall face and by 31 % for 1043 longwall face of the Zakhidno-Donbaska mine. This level of influence (by an average of 30 – 40 %) should be taken into account when substantiating the appropriate parameters for site outgassing technology. Also, taking into account the identified tendencies, it can be recommended to limit the rational step l_2 values to an interval of $9 \leq l_2 \leq 13$ m, where the outgassing coefficient K_{out} has increased values (figure 9).

Summarizing the experimental research results, it can be argued that they, based on

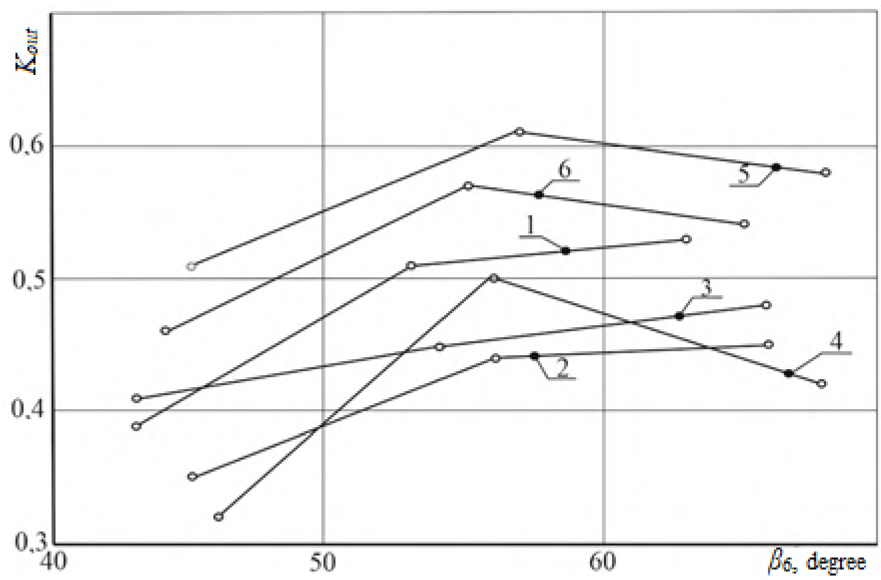

Figure 8. Patterns of influence of the gradient angle β_6 (to the coal seam stratification plane) of outgassing wells on the outgassing efficiency: 501 (1), 503 (2), 962 (3) and 1124 (4) longwall faces of the Heroiv Kosmosu mine; 885 (5) and 1043 (6) longwall faces of the Zakhidno-Donbaska mine.

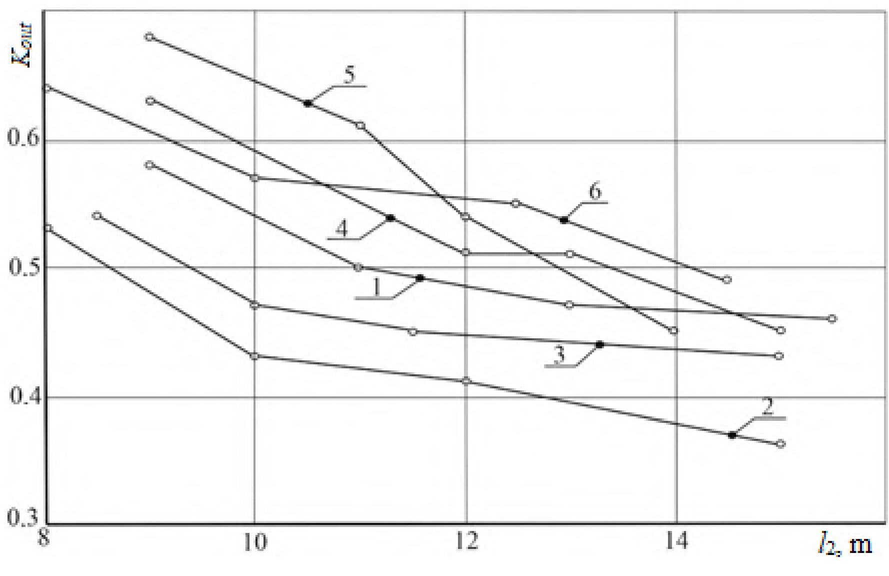

Figure 9. Patterns of influence of the step l_2 of drilling wells on the outgassing efficiency: 501 (1), 503 (2), 962 (3) and 1124 (4) longwall faces of the Heroiv Kosmosu mine; 885 (5) and 1043 (6) longwall faces of the Zakhidno-Donbaska mine.

indirect parameters (outgassing coefficient), confirm the general tendencies in the influence of geomechanical-technological factors on the site outgassing efficiency during high-velocity mining of coal seams in the Western Donbas mines. The feasibility of using the proposed recommendations (based on the FEM modeling results) for the selection of site outgassing parameters, which will allow an average of a third increase in the productivity of stoping faces using the so-called "gas factor", has also been confirmed.

7. Methodology for selecting site outgassing parameters

The algorithm for calculating the parameters for site outgassing well location is described in detail earlier, and now some clarifications are given based on the experimental research results, since the study of the outgassing process at six extraction sites of two mines has not revealed fundamental differences with the FEM modeling results [50, 51].

The calculation is performed on the basis of mining-geological prediction data (depth of stoping operations, texture and mechanical properties of coal-overlaying formation rocks), the longwall face passport (planned indicators of its advance, schemes for placing equipment at the end longwall face sections) and the passport for draining-out of gases (scheme for placing drilling equipment). This information is the initial data, based on which the following sequence of calculations is accepted.

1. The outgassing well route gradient angle β_4 along the strike of the coal seam is calculated by the formula $\beta_4 = \arctan \frac{h_s}{h_s \cot \beta_3 + C_1 + W_{pr} + Weq}$ and the outgassing well turning angle in the direction to the coal seam rise is calculated by the formula $\beta_5 = \arctan \frac{C_1 + Wpr + Weq}{h_s \cot \beta_1 + C_2 + L_{eq}}$ To do this, it is necessary to calculate intermediate parameters using the formulas (1) – (10).
2. The outgassing well route gradient angle β_6 to the coal seam stratification plane is determined by the formula $\beta_6 = \arctan \frac{h_s \sin \beta_5}{C_1 + W_{pr} + Weq}$. It is preferable for the calculated value of β_6 to fall within the experimentally determined rational range $55^{\circ} \leq \beta_6 \leq 65^{\circ}$; then the reliability of our recommendations increases.
3. The step l_2 of drilling outgassing wells is calculated by the formula $L_2 = a_s$; before this, it is necessary to calculate the intermediate parameter a_s using the formulas (11) – (15). To increase the reliability of recommendations for choosing the l_2 value, it is preferable that it be in the range of $9 \leq l_2 \leq 13$ m.
4. The time for drilling the next well is determined provided that the distance of its mouth from the fencing of the powered support approaches the value l_1 determined by the formula $L_1 = h_s \cot \beta_1 + C_2$.
5. The outgassing well length l_w is determined by the formula $L_w = \frac{H_m}{\sin \beta_6} + \Delta_{ov}$. However, at the longwall face advance velocities of $V_l \geq 7$ m/day, the well length can be reduced by 25 – 40 %, since the coal-overlaying formation stratification height is limited.
6. The calculation parameters for outgassing well location schemes are tested for 20 – 30 m of the extraction drift length. If necessary, well drilling parameters are adjusted.

8. Conclusions

A complex of mine instrumental observations of gas release and gas trapping processes in the site outgassing technology allowed to obtain multifactorial information on the influence of geomechanical-technological factors on them, conduct a comparative analysis of the analytical and experimental research results. This eventually contributed to the development of a methodology for selecting rational parameters for outgassing well location schemes for highly productive mining of the Western Donbas coal seams.

A new methodology has been developed, which differs from the existing ones by taking into account the multifactorial geomechanical-technological factors of outgassing the extraction sites. Three main methodological provisions have been substantiated on the basis of performed FEM analytical research. They are included in the newly created algorithm for conducting mine experiments, consisting of three interconnected stages: general verification of the reliability of recommendations generated analytically using FEM; assessing the objectivity of the patterns of influence of geomechanical factors on the site outgassing process; studying the influence of a number of its technological parameters on the outgassing process efficiency.

At the general experimental assessment stage of the objectivity of recommendations, the main tendency is consistently visible (for various mining-geological conditions): the outgassing coefficient according to the recommended parameters is higher than that corresponding to outgassing well location schemes existing in mines. The objectivity of this conclusion is confirmed by experimental measurements at six extraction sites of two mines – the range of relative increase in the outgassing coefficient ranges from 19 % to 123 %.

There is a significant influence (up to 35 – 60 %) of the coal-overlaying formation texture on the outgassing coefficient; this influence is independent of other geomechanical-technological factors of mining the Western Donbas coal seams.

It has been experimentally determined that an increase in the longwall face advance velocity V_l (by an average of 30 – 45 %) contributes to an increase in the gas trapping efficiency by an average of 25 – 40 % in various mining-geological conditions of mining the Western Donbas coal seams. That is, the tendencies in the same direction of increasing the coal mining productivity have been identified: the growth of V_l leads to a decrease in the methane inflow into the adjacent mine workings, and this, in turn, substantiates the possibility of accelerating the longwall face advance.

The influence of the well gradient angle β_6 on the outgassing coefficient is by an average of 20 – 30 % under different mining-geological conditions of mining the Western Donbas coal seams.

The step of drilling l_2 of outgassing wells along the extraction drift has an average level of 30 – 40 % influence on the outgassing coefficient; therefore, the parameter l_2 should be taken into account when substantiating the technological factors of site outgassing technology. Based on the experimental research results, a step l_2 in the range of $9 \leq l_2 \leq 13$ m is recommended, where K_{out} has increased values.

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Application of geometrization to estimate mineral deposit reserves

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Application of geometrization to estimate mineral deposit reserves

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Abstract. The article discusses aspects of geometrization of mineral deposits. Particular attention is paid to the geometrization of mineral reserves. Various geometrization methods allow one to obtain ambiguous results, depending on the geological structure and spatial location of mineral deposits. Various options for estimating mineral reserves are considered and the method for optimal estimate is described. The method makes it possible to estimate reserves of mineral deposits of a complex configuration, find the most probable strike line of such deposits and clarify their contour. The method is based on choosing the optimal direction of vertical cross-sections and the distance between them. The influence of the shape of a mineral deposit on the accuracy and completeness of reserve estimate was considered. The experiments were carried out theoretically and practically in various mining and geological conditions. A more accurate estimate of mineral reserves is made using geostatistical and heuristic methods developed by the authors of the study. The described methodology for geometrization and estimate of mineral reserves was applied at mining enterprises in Ukraine and gave effective and accurate results. This made it possible to increase the efficiency of mining planning and the rationality of the mining enterprise.

1. Introduction

The operation of a mining enterprise is entirely dependent on the efficiency of mining [1]. Various methods for estimating mineral deposits are aimed at determining the properties of minerals and rock masses. Geometrization of mineral deposits ensures the completeness of the estimate of mineral deposits [2, 3].

Technological properties of rocks are an important aspect of the geometrization of mineral deposits [4]. The methods for such geometrization are determined by the composition and properties of the rock mass [5]. In this case, it is important to take into account all interacting factors affecting the efficiency of mining [6].

Improving the technology of mining and the extraction of mineral resources requires a comprehensive mining-geometric estimate of geological and technological objects. Increasing the efficiency of mining operations is based on comprehensive information obtained by geometrization methods [7, 8].

A large number of studies are aimed at determining the state of the massif and changes in its state during mining operations [9]. Such studies can be based on determining the geophysical parameters of the rock mass, the mineralogical composition of minerals, as well as the technological properties of rocks [10].

The sustainable development of the mining industry is based on increasing efficiency and mining operations [11]. During mining operations, it is necessary to comply with environmental protection requirements. Achieving high results is closely related to an integrated approach to the geometrization of mineral deposits [12]. The issues of geometrization of deposits in complex mining and geological conditions are especially relevant.

Objective planning of mining operations [13] and productive work of a mining enterprise is based on a clear understanding of the geometric position of the mineral resource and mine workings [14,15]. Long-term and current planning of the work of a mining enterprise is an urgent task of mining production.

The creation of promising and effective systems for the mining of mineral deposits widely uses mining-geometric methods for estimating technological processes and their impact on the rock mass, providing comprehensive monitoring of mining operations [16, 17].

Various conditions for the mining of mineral deposits can be systematized by taking into account and monitoring the mining and geometric parameters of individual sections of the mineral deposit [18]. The result of geometrization in this case will be a clear idea of the quality and quantity of minerals in different areas of the deposit [19].

Prospects for the development of methods for mining iron ore deposits are especially important in modern conditions [20]. The method for geometrization of iron ore deposits is very relevant at all stages of a mining enterprise and covers a wide range of studies [21]. Rationalization of the work of a mining enterprise and the use of subsoil is achieved through a mining-geometric estimate of the deposit [22].

One of the most interesting areas of geometrization of mineral deposits is the estimate of their reserves [23]. Integrated use of mineral deposits is an integral part of mining. Research aimed at the most rational use of deposit resources is the most important direction in geometrization of mineral deposits [24].

Geostatistical and heuristic methods for estimating mineral reserves are one of the most promising areas of research [25, 26]. These methods are accurate, easy to use, and easy to modify [27, 28].

Thus, the study is devoted to the methodology for geometrization of mineral deposits using geoinformation systems. Much attention is paid to the geometrization of mineral deposits of a complex configuration, as well as the selection and modification of the optimal method for their geometrization in various mining and geological conditions.

2. Methods

The existing methods of geometrization are based on the idea of placing indicators of a mineral deposit in the form of a geochemical field, which can be described by some function of the coordinates of a point in space $P=f(x,y)$ or $P=f(x,y,z)$ [29]. There is an assumption that the function P satisfies the conditions of finiteness, uniqueness, continuity and smoothness. In subsurface geometry, the method of isolines is used as one of the main methods of depicting surfaces of topographical order [30].

Depending on the degree of exploration of the deposit, the exploration network may use regular testing, irregular testing, and continuous testing. The implementation of the isoline method depends on the parameters of the geological exploration network and the characteristics of the variability of the deposit indicators. The main methods for constructing isolines include:

the method of invariant lines and slopes; polyhedron method; method of profiles; statistical and geostatistical methods; reverse distance methods, etc. Their logical analysis for the purpose of formalization made it possible to single out the following main computational, graphic and heuristic procedures for geometrizing the deposit. These include the following procedures: mining geometric analysis of the initial data and the choice of a specific method of graphic modeling or their combination; conversion of initial data into an induced network; construction of isolines in a linear approximation followed by smoothing; creating a graphic image.

As a result of the mining and geometric analysis of geological data, the general regularities of the location of the indicator in the subsoil are established. At this stage, the invariant lines and slopes of the depicted surface are outlined, the boundaries of the geometrization areas are determined. It is this stage that is the most difficult to formalize for the use of geographic information systems.

The results of studying the variability of the indicator provide additional data for mining and geometric analysis. If the invariant lines are close to straight lines, then when studying variability, the main directions of anisotropy approximately coincide or are perpendicular to the invariant lines. Quantitative estimates of the parameters of variability are used to determine the height of the section of the isolines.

The choice of the method for construction of isolines is determined by the results of mining and geometric analysis and studies of variability. Polygon, invariant lines, and slope methods are commonly used to construct structural plans with an irregular scout network. Since qualitative indicators usually contain a significant part of a random component, the statistical window method or its modification is used to display their properties. The size of the smoothing window can be determined based on the height of the section of the isolines.

The transformation of the original data into a regular rectangular or square network is carried out using analytical models of the placement of indicators or smoothing methods, including methods of optimal statistical interpolation.

Thus, regardless of which data network is used (triangular or rectangular), the isoline coordinates are determined at the first stage using interpolation on the edges of the network along two adjacent nodes. After that, the broken isolines are smoothed out, that is, a nonlinear approximation of the depicted surface is performed.

For volumes that correspond to sample sizes, Krige developed a method for estimating the content at a given point by averaging the content at the nearest sample points with weights that decrease with increasing distance from the point. This method was called kriging [31]. To use kriging, it is necessary to estimate the variogram, which is a correlation function, from the test data. The accuracy of the calculation of mineral reserves depends on the correct estimation of this function. In this regard, the issues of changing these functions depending on the geometry of the samples, the orientation of the sampling lines in relation to the ore body, etc. There are empirical formulas to account for the effect of sample geometry on the appearance of these functions, but the effectiveness of their use remains controversial. However, this issue significantly affects the solution of kriging problems. In a more general form, it can be stated as the study of the type of these functions and content histograms depending on the change of the volume within which the content is evaluated. There is no definite solution to these issues, and the mentioned problems remain unresolved to this day. However, the ideas listed above served as a prerequisite for the development of technologies for building mathematical models of deposits.

The mathematical model of the deposit is a basic element of the method for estimating conditions and counting reserves, because it is used to geometrize reserves and build blocks, find the optimal position of contours of mining, calculate mineral reserves, etc. The mathematical model of the deposit, when solving many tasks of technical and economic substantiation of conditions and calculation of reserves, replaces the base of primary data of exploratory testing, on the basis of which the tasks of calculating mineral reserves are solved.

Most of the listed operations in graphic modeling are quite easily formalized, with the exception of a number of heuristic procedures. So, for example, for the selection of invariant lines and slopes, as well as for the triangulation of geological exploration networks, additional geological information must be used.

The analysis of logical connections between computational, graphic and heuristic procedures determines the principle of building mathematical support for the tasks of graphic modeling of the deposit. Mathematical support of automated geometrization contains programs of three levels: basic, functional and applied. The division of mathematical support into levels corresponds to the degree of detail of the displayed graphic information.

Basic programs allow construction of the simplest geometric elements.

Functional programs are developed taking into account the content of applied tasks. Functional mathematical support for graphic modeling tasks includes: construction of coordinate grids with coordinates along the perimeter of the grid; construction of test plans with plotting of wells, their names, content of components; construction of the main elements of mining plans; coordinate transformation (affine, functional, etc.); design of graphic documents; drawing graphs of functions that are given analytically in an explicit form and parametrically; drawing graphs of functions, which are given in the form of a table, using various interpolation methods.

Applied graphic modeling programs provide drawing of isoline plans by various methods, geological sections with isolines of quality indicators, plans of mining works, block diagrams, three-dimensional images of surfaces of topographical order, models of mining and geological objects in axonometric projections. Given the fact that different methods of graphic modeling contain identical interpolation procedures (transformation of coordinates, smoothing of isolines, signing of isolines), the most rational principle of forming a package of application programs is modular.

In figure 1, as an example of performed geometrization presents the graphical result of geometrization of the deposit, which is mined by the Slavyansky chalk-lime plant quarry. The combination of mining-geometric methods used makes it possible to geometrize a mineral deposit and build a digital model of a mineral deposit.

Modeling and evaluation based on a multidimensional heuristic forecasting algorithm based on the use of a polynomial of arbitrary degree developed by the authors has a number of advantages over existing one-dimensional and multidimensional methods. The accuracy of modeling and the efficiency of using available geological information are significantly increased through the quantitative expression of either previously unknown or known qualitative genetic relationships between indicators [32].

The algorithm in general can be depicted in the form of a block diagram (figure 2).

The flowchart is a generalized illustration of the sequence of operation of the algorithms included in the multidimensional heuristic forecasting algorithm. It can be seen that the algorithm as a whole has a cyclic structure. The cycles are organized in such a way that when they are repeated, the forecast function becomes more complex, its accuracy and adequacy to the real pattern of placement of the forecast indicator increases. The criterion for stopping the algorithm can be the absence of an increase in the accuracy of the predictive function at the next iteration, or the achievement of the specified accuracy.

Using this method, you can identify almost any known functional dependence. Although the method does not use trigonometric functions, any of them can be represented as a power series and calculated with a given accuracy. An example of this is the Maclaurin series expansion of the function of sine, cosine, natural logarithm, etc. If within the considered mineral deposit there is an intermittent pattern of distribution of the predicted indicator, then the principle of conditional division by zero is used. In this case, the function is assigned an optimally fixed value. This method was first used to create this algorithm. This method is the first to consider

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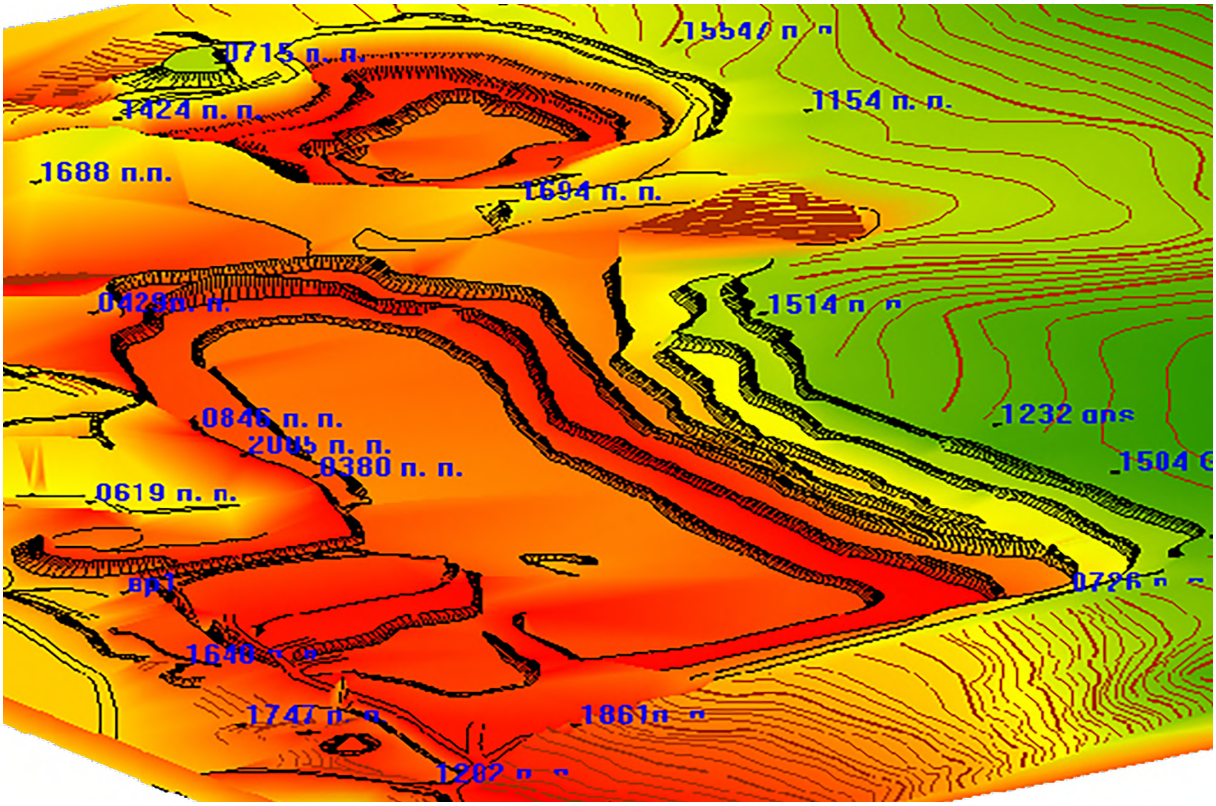

Figure 1. Digital graphic model of the Slavyansky chalk-lime plant quarry.

a mathematical method for determining the sensitivity of numerical coefficients, which makes it possible to quickly estimate the gradient of a function change and, therefore, the ability to select the coefficient to which the function is most sensitive. This is a simplified functional model of empirical evaluation. The algorithm for grouping data according to deviation criteria for constructing individual forecast functions is also considered for the first time in this method.

3. Results and discussion

The methodology of geometrization developed by the authors of the study is a set of methods that ensure obtaining the most complete and objective estimate of geological and mining-technological indicators of mining operations. The use of geoinformation systems such as Micromine, K-Mine, Surfer, AutoCad provides an efficient automated process of deposit geometrization based on promising and accurate mathematical methods implemented in these systems. The most significant is the geometrization and estimate of mineral reserves. The efficiency of the mining enterprise depends entirely on the accuracy and completeness of the estimate of the deposit's reserves.

Geometrization of reserves of minerals of a complex configuration requires modernization and refinement of the methodology for estimating reserves in complex areas of the deposit. Methods for geometrization of mineral deposits of a complex configuration are an integral part of the methodology for geometrization of the deposit. This method was applied at the mining enterprises of Ukraine. For example, consider a deposit of a complex configuration, which is mined by the "YUZHNIY GOK" quarry.

There are several problematic issues in the method of parallel vertical cross-sections, which is quite common in production. It is necessary to pay attention to the impossibility of calculating

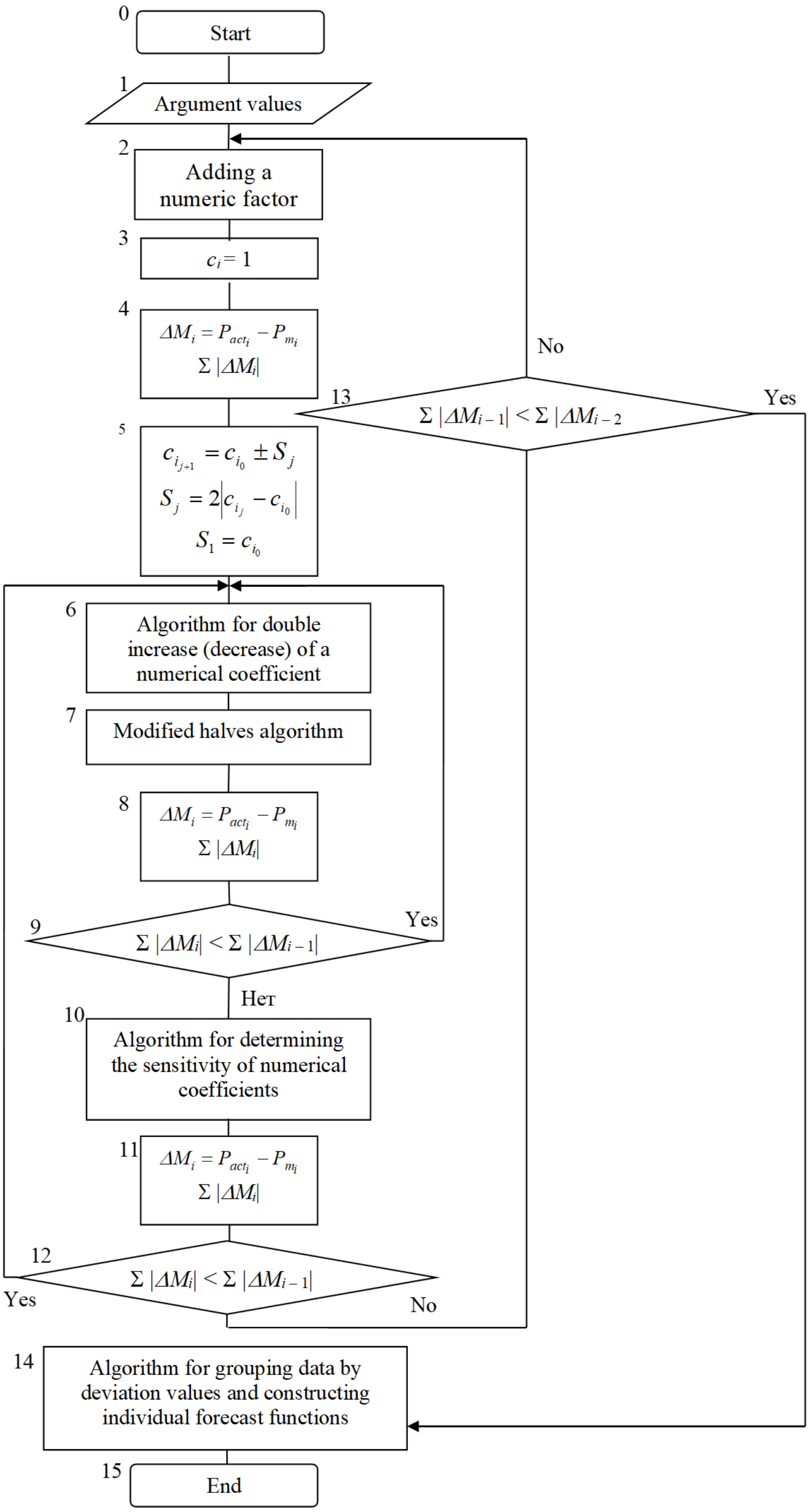

Figure 2. Multidimensional heuristic forecasting method: $\triangle M$ – the deviation of the modeled function; S – the intermediate value of the simulated function; c – the modeled indicator.

the volumes in the extractable blocks of a complex configuration. It is impossible to optimally locate the mineral deposit strike line, perpendicular to which cross-sections are built, without violating the condition of their parallelism. The optimal directions of the location of fragments of the mineral deposit strike line in separate parts of the block do not lie on the same straight line. The use of one line, under the condition of fixed distances between cross-sections, leads to an increase in counting errors.

A known situation is when the planned position of the mineral deposit strike line is clearly established. According to such an arrangement of cross-sections, it is convenient to calculate the volumes of several figures with the possibility of their constant accumulation. It is possible to perform different counting options, for example, at different time intervals. However, due to this, variants with a significant loss of accuracy are possible. The error mainly occurs in cases where the blocks or their parts are not located across the cross-sections, but along or at an angle close to it. At the same time, significant changes in the configuration of the contours of the calculated block are possible between cross-sections, and the total volume of the part of the block between adjacent cross-sections can be calculated with an unacceptable error.

One way to solve this problem is to add intermediate cross-sections to reduce the distance between the cross-sections. Thanks to this, the error is reduced.

There is an assumption about the existence of the optimal direction of the arrangement of cross-sections in the method of parallel vertical cross-sections when the distance between adjacent cross-sections is reduced to the required level. It is possible to find the optimal distance between the cross-sections and the optimal direction of the cross-sections, at which the volume of mineral in the block will be maximum. This will mean that the cross-sections cover the area of the block as much as possible. This will also make it possible to more accurately outline mineral deposits. In this case, you can get more accurate results of the interpolation of the conventional contact line.

To study the change in volume from the angle of rotation of the planned position of the cross-sections and the distance between them, an experimental block was modeled. Through the center of gravity of the block in the XY plane and parallel to the X axis in the conventional coordinate system, the probable mineral deposit strike line was drawn, perpendicular to which cross-sections were separately constructed after 20 meters. Based on them, the volume was calculated, in the form of a report, which consisted of a table with calculations (table 1) and constructed cross-sections on the appropriate scale (figure 3), for the possibility of checking the obtained results.

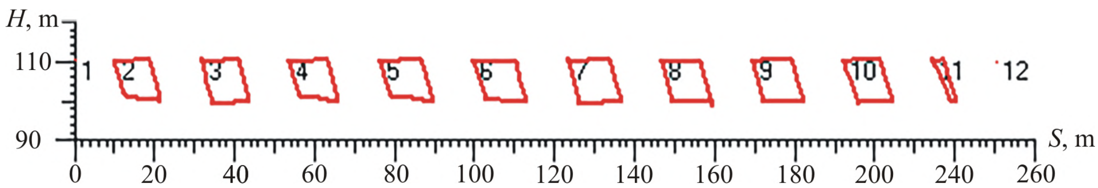

Figure 3. Vertical cross-sections for volume calculation, the distance between which is 20 m: S – the distance along the mineral deposit strike line, m; H – the vertical distance, m.

The next step is to calculate the volume of this block relative to the Y axis. The results obtained from the report according to the previously described template were compared with the previous ones. The volume was calculated in the direction where the angle of the plan position of the cross-sections is equal to the average angle of the two previous angles. Analyzing the results of the previous calculations, the rotation of the cross-section line in the plan is continued in such a way that the cross-section line turns clockwise relative to the center of gravity by one degree, and the calculations are repeated. The process is repeated until the line is rotated 180°.

Table 1. Calculation of volumes by the method of parallel vertical cross-sections with a distance between cross-sections of 20 m.

Section number	Area, m^2	Section number	Area, m^2	Distance, m	Volume, m^3
1	0.00	2	201.77	16.87	1134.39
2	201.77	3	247.67	20.00	4486.61
3	247.67	4	223.37	20.00	4708.27
4	223.37	5	237.70	20.00	4609.96
5	237.70	6	256.99	20.00	4945.66
6	256.99	7	279.48	20.00	5363.07
7	279.48	8	256.65	20.00	5359.62
8	256.65	9	266.57	20.00	5231.91
9	266.57	10	236.68	20.00	5029.62
10	236.68	11	40.71	20.00	2503.68
11	40.71	12	0.00	6.82	92.51
Total volume. m^3:					43465.31

In this way, you can consider all possible calculation options (figure 4).

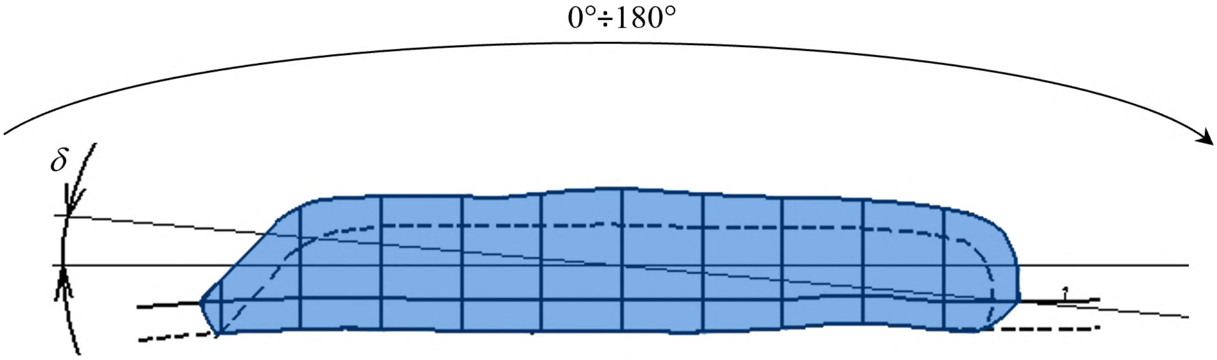

Figure 4. Simulated experimental block: δ – the angle of rotation of the cross-section line, which varies from 0 to 180 degrees. The experimental block is indicated in blue.

First, the volumes were calculated at a distance between cross-sections of 20 m. To check the assumption described above, the distances between cross-sections are reduced. In the same way, preliminary calculations are performed for distances between cross-sections of 10 m, 5 m, 2 m and 1 m.

Further reduction of the distances did not result in significant differences at these volumes. The dependence study is completed at a distance between cross-sections of 1 m.

For each stage of the calculation, a report containing a table containing data on the numbers of cross-sections, their areas, and the volumes between two cross-sections was generated. Based on these data, graphs of dependencies were constructed, which indicate that the angle of rotation of the cross-sections ceases to play a significant role when the distances between the cross-sections are reduced to the optimal value. For example, for the selected block, it is advisable to use a distance between cross-sections equal to one meter. You can make sure of this visually by looking at the combined graph of the dependence of the volume of the block on the angle of the cross-sections strike line of at different values of the distance between the cross-sections (figure 5). Line 20, which corresponds to the dependence at distances between cross-sections of 20 m, has the largest error of the volume and is not acceptable for the use of an arbitrary angle. The following lines corresponding to distances of 10 m, 5 m and 2 m are also inadmissible. However, there is a tendency to straighten the line at the mark of the true volume. Lines 1 and 2 almost do not differ from each other and have almost the same volume value for all variants of the angle of rotation, which confirms the assumption. However, it is line 1 that has the smallest deviation from the real volume, and therefore the distance between the cross-sections, which is equal to one meter, can be used for an arbitrary plan angle of the location of the cross-sections.

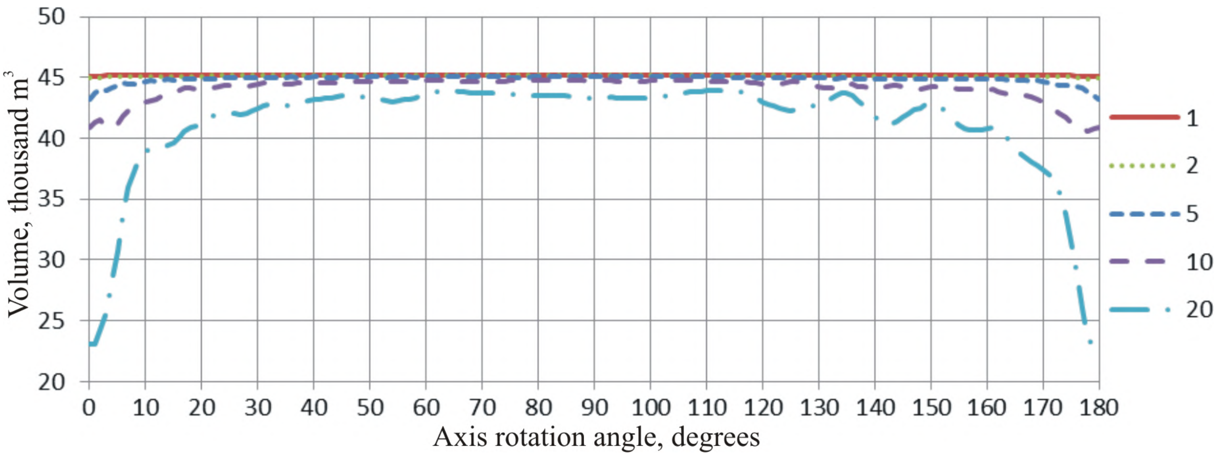

Figure 5. Graph of the dependence of the volume of the block on the angle of the cross-sections strike line at different values of the distance between the sections: 1 – the dependence at a distance of 1 meter; 2 – the dependence at a distance of 2 meters; 5 – the dependence at a distance of 5 meters; 10 – the dependence at a distance of 10 meters; 20 – the dependence at a distance of 20 meters.

To find out the influence of different configurations of mineral deposits on the accuracy of volume calculation, three configurations of blocks at different horizons were chosen: a flat elongated block, a block with a sharply rounded configuration, and an intermediate variant (figure 6). For each of the blocks, the volume was found at different values of the distance between the cross-sections and different values of the angle of the cross-sections strike line.

The results of estimating the reserves of the direct configuration block did not significantly differ from the results of estimating the reserves of the previous block, which was created to study the dependence of the volume on the influence of the planned location of the cross-sections and the distances between them. Therefore, let's dwell in more detail on the round and convex block configurations.

For the round configuration of the block, according to the previously described method, the results were also obtained, which were tabulated for the purpose of the subsequent comparison of similar data and their statistical analysis to estimate the accuracy of the conducted studies. Similar actions were performed for the block with the convex configuration. To compare the results obtained by different block configurations, the following graphs were constructed (figure 7, figure 8).

4. Conclusions

Thus, the described method makes it possible to estimate and outline deposits with a complex nature of mineral placement. This is realized by choosing the optimal direction of construction of cross-sections, in which the maximum amount of minerals falls into the plane of the cross-sections. At the same time, the optimal distance between cross-sections depends on the quality

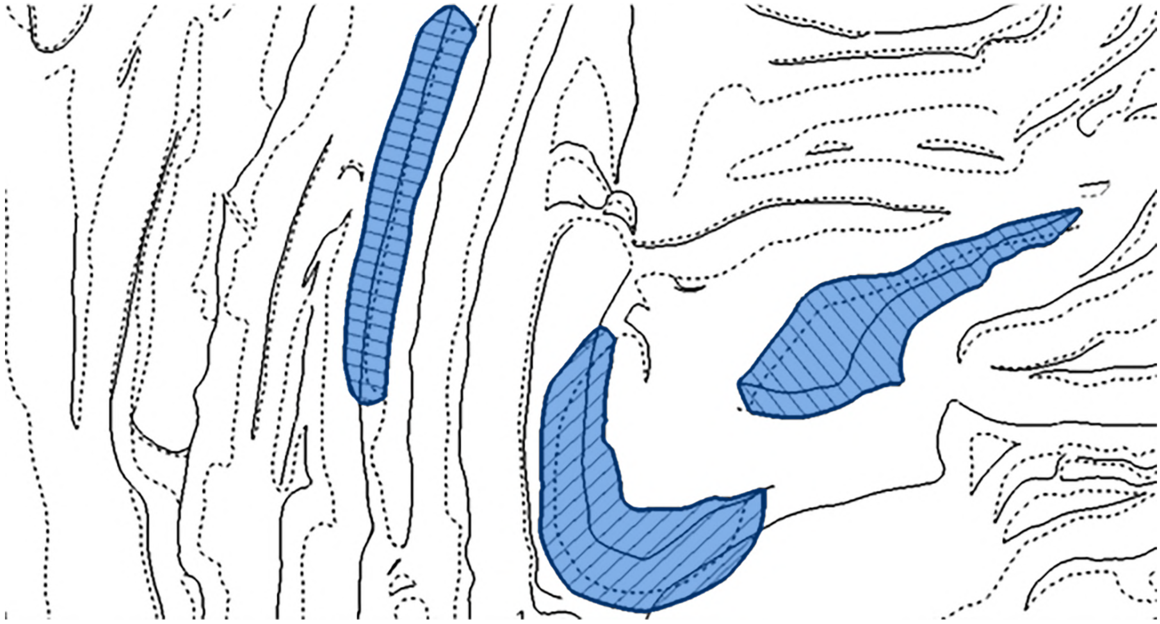

Figure 6. Blocks of various configurations with cross-sections for volume calculation. Experimental blocks are indicated in blue.

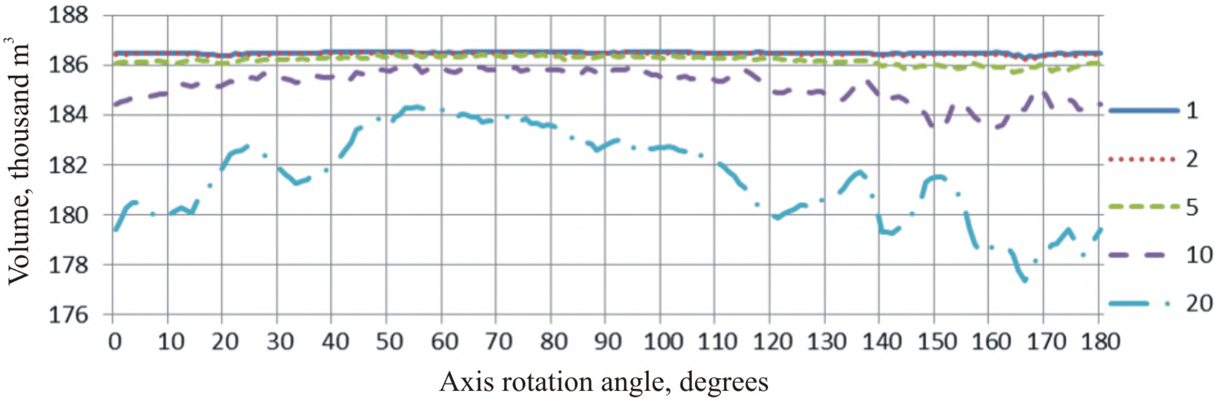

Figure 7. Graph of the dependence of the volume of the block of the circular configuration on the angle of the cross-sections strike line at different values of the distance between the cross-sections.

of geological information, which is the basis of the geometrization of the mineral deposit. The quality of geological information can be estimated using geostatistical methods, which include the kriging method. The methodology of geometrization, developed by the authors of the work, widely uses geoinformation systems, which implement geostatistical methods for geological information estimate. The multidimensional heuristic method for mineral deposit estimate developed by the authors makes it possible to construct functional dependencies of the placement of indicators of a mineral deposit. In general, the set of methods included in the methodology increases the accuracy of the estimation of mineral reserves, and makes it possible to estimate the reserves of a mineral deposit with an error 6 – 8%.

This makes it possible to increase the efficiency of planning of mining operations and the rationality of the operation of the mining enterprise.

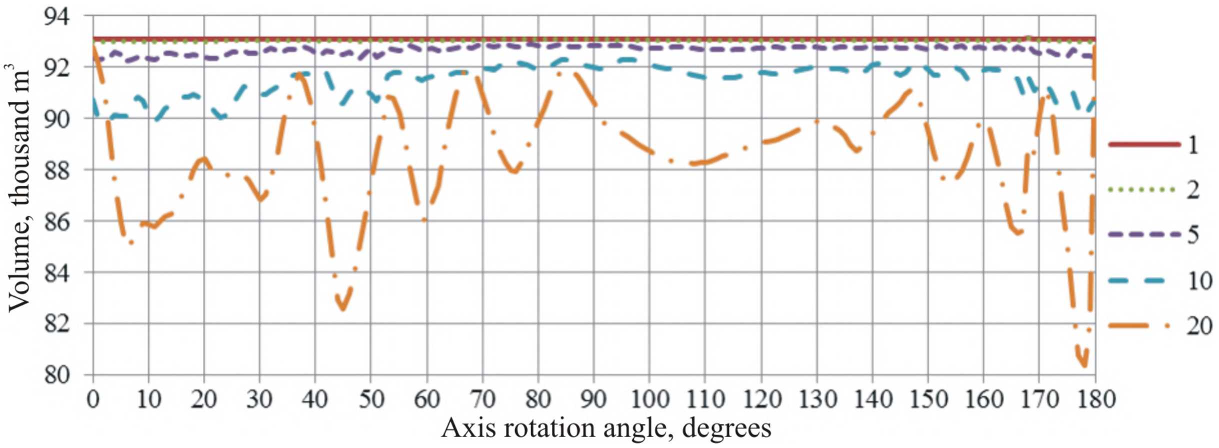

Figure 8. Graph of the dependence of the volume of the block of the elongated configuration on the angle of the cross-sections strike line at different values of the distance between the cross-sections.

The further direction of research consists in the development of methods that are included in the methodology for geometrization of mineral deposits, and increasing its accuracy and universality. The most promising areas of development are geostatistical and heuristic methods for mineral deposit estimate.

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Research on influence of stress-strain evolution in immediate floor before and after excavation face on origin floor heave in coal mines roadways

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Abstract. The floor heave is one of the most acute issues of underground mine roadways stability problem. With an increase in mine depth, the floor heave becomes more dramatic. Analysis shows that rock bolts reinforcement is the most advanced and worldwide method of floor heave control. The current mine roadway support systems in Ukraine usually do not provide measures to floor heave control. As a result, floor heave values exceed 0.7-1.0 m, which leads to disruption of transport chains and failure of ventilation regime. In this paper, for the typical conditions of coal mines located in Pokrovsky, Dobropilsky districts and Western Donbass, stress-strain evolution in roadway's bottom before and after excavation face was studied. Ansys code was used to analyze the evolution of stress and strain in immediate floor of roadway before and after excavation face. It was found that rocks in immediate floor undergo cyclic loading and alternating strains. Before and after excavation face a zone of increased stress and a stress relief zone are formed respectively. Thus, in the immediate floor behind the excavation face cracks are formed and structurally defects are branched. This initiates the origin of floor heave process. The control of the immediate floor delamination after excavation face can be ensured by a timely installation of rock bolts in the excavation face with their inclination to roadway face. The most appropriate bolt inclination coincides with the contour of the stress concentration zone, which can be determined from the results of numerical modeling.

1. Introduction

The post-war reconstruction of Ukraine will undoubtedly require a powerful energy and metallurgical growth. Therefore, it is most likely that the roadmap for the transformation of the Ukrainian coal industry will be adjusted, at least in the near future. The current shortage of energy carriers in the country, caused by Russia's military aggression, shelling of critical energy infrastructure, insufficient gas and oil resources, and the European energy crisis, can only be overcomed by increasing coal production. Thus, despite the global trend of decarbonization, increasing the productivity of coal production in wartime and the period of post-war recovery is an urgent task of the Ukrainian energy industry.

In order to ensure the rhythmic operation of coal mines, it is necessary to solve the issue of mine ventilation, organization of main and auxiliary transport in a timely manner. The permissible methane or flammable gas concentrations in the coal mine, the rhythm of mine roadway preparing and coal mining directly depends on the mine roadways state.

Among the issues of underground mine roadways stability , the most acute today is the issue of floor heave control. About 70-80% of mine roadways in Ukraine are repaired due to dramatic floor heave [1]. Same repairing rate is noted by researchers from other countries [2]. With an increase in mine depth, the problem of roadway floor stability becomes even more urgent. The current methods of excavation and supporting of mine roadway in Ukraine usually do not provide floor support system, or additional measures to control the floor deformation and failure. This leads to the disruption of transport chains, the reduction of the cross-section of the mine roadway and, accordingly, the failure of ventilation regimes. The floor heave control is carried out primarily by floor digging method. The floor heave problem is typical not only for the mine roadways. This phenomenon is observed during the tunnel construction, civil engineering in mountains, construction of another underground objects [3, 4].

Currently, many scholars have conducted extensive research on the floor-heave mechanism through in-situ monitoring, laboratory tests, physical and numerical simulation. The results indicated that the floor heave is mainly related to factors such as in-situ stress field, rock mass type, water inflow, and mine roadways support design. Faria Santos and Bieniawski [5] summarize main floor heave mechanism, including bearing capacity failure, buckling, and swelling (figure 1).

Bearing capacity failure of floor rock happens when the vertical stress that transmitted from roadways sidewall to floor, exceeds the load-bearing capacity of rock mass in immediate floor [6]. Swelling is observed as a result of exposure of clay-rich materials, such as mudstone, claystone, and shale, to moisture [5]. Buckling usually occurs where the rock mass of immediate floor is stronger than the strata underneath. Buckling is typically observed where the high horizontal stress initiates floor layer moving [7]. Anyway, a significant cause of floor heaves is alters of the natural equilibrium state and stress redistribution in the surrounding rock [8, 9]. There is the reason why the main efforts of scholars in recent years have been directed to the stress and strain study of the surrounding rock. Usually such studies are carried out by numerical simulation.

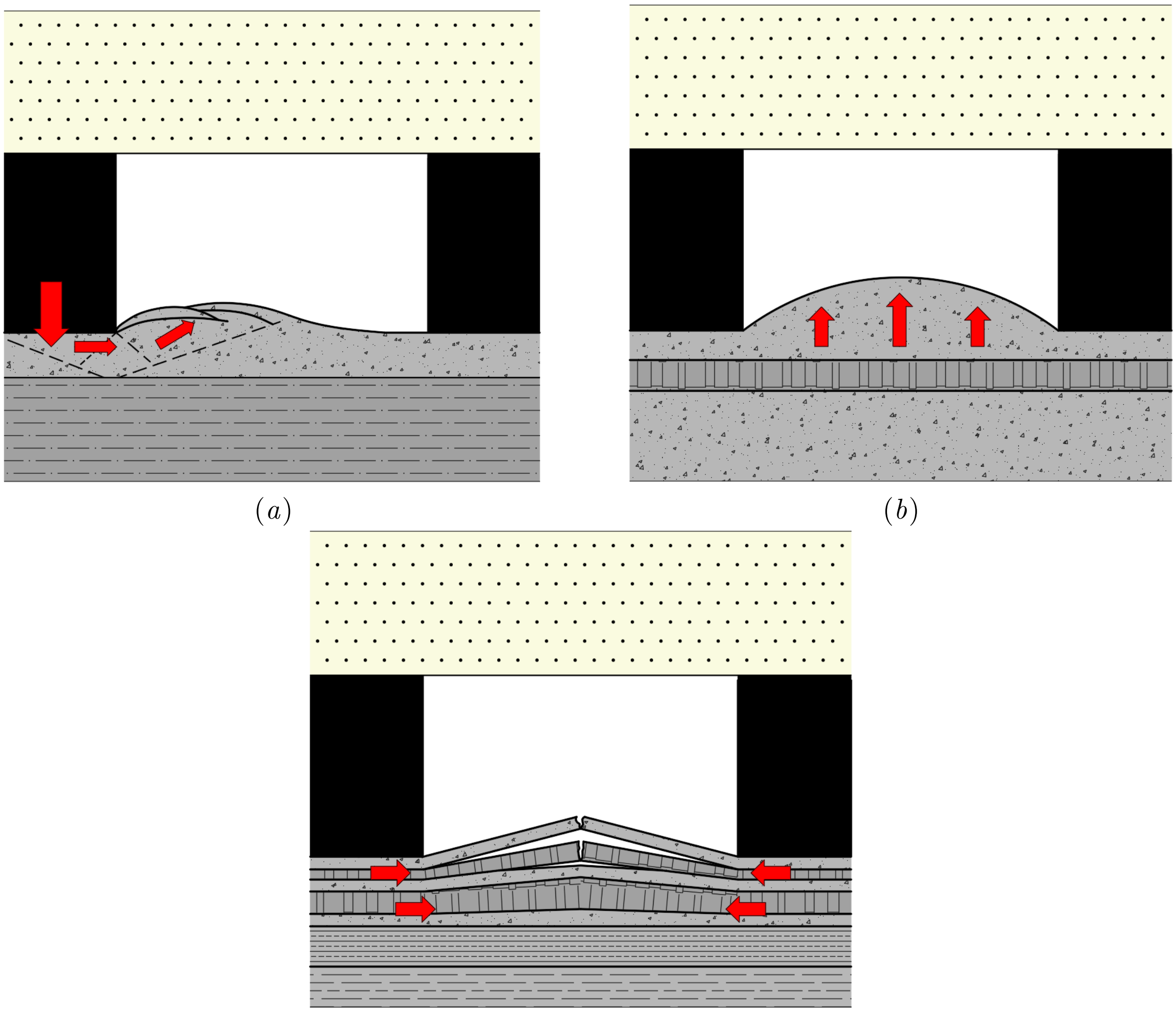
Zhao et al. [10] presented the simulation results of the U-shaped steel closed support that is able to control the floor heave of roadways. The numerical simulation was conducted using the finite difference software FLAC3D.

Liu et al. [11] analised floor stress distribution law after mining in the surrounding rock, that was verified by FLAC3D numerical simulation. Zhou et al. [12] put forward three support optimization schemes, simulated the support effect of each scheme, and finally determined the best support optimization scheme. In this paper, the analysis of the distribution plastic area, stress nephogram, and displacement field simulation results in surrounding rock was proposed by using FLAC3D. Małkowski, Ostrowski and Stasica [13] used a Phase 2 program for numerical simulations of two-dimensional deformation of roadway floor heave in dry and waterlogged conditions. Qi et al. [14], and Zhang et al. [15] simulated the failure mechanism of soft rock roadway by UDEC.

Sakhno and Sakhno [16] used ANSYS code to simulate the floor heave control by the rock bolts reinforcement technology.

Usually, during such studies, the stress-strain field in surrounding rocks in the cross section of mine roadway is analyzed. At the same time, the change in the stress field immediately after the equilibrium state alter before and after excavation is not taken into account. Nevertheless, the previous research overlooked the evolution of stress-strain state in surrounding rock under the excavation redistribution stress. This phenomenon is also not taken into account during analysis of the effectiveness of floor heave control methods.

Floor heave control methods are mainly related to inverted arch construction, floor concrete beam or circular closed support construction [17, 18], cutting stress relief slot in the floor or wall of roadway [19, 20], and reinforcing of immediate floor [21, 22]. Rock bolts reinforcement is the most advanced and worldwide method of floor heave control [23].



(a) *(b)* *(c)*

Figure 1. Floor heave mechanisms: (a) bearing capacity failure, (b) swelling, (c) buckling.

In this paper, for the typical conditions of coal mines located in Pokrovsky, Dobropilsky districts and Western Donbass, stress and strain evolution in immediate floor before and after excavation face was studied. This study provides a characteristic of the underground roadway excavation influence on stress-strain state of immediate floor and its delamination. This paper proposes floor support method based on rock bolts installation in the stress concentration zone before the excavation face.

2. Engineering background

The analysis of geological maps and the current state of the coal industry shows that mines of Pokrovsky, Dobropilsky districts and Western Donbas are the most perspective for the development of coal mining. Mines located in the occupied territory require extremely large investments, which is not advisable when the mine fund is worn out by 80-90%. In the current balance of coal production in Ukraine: 65% is the production of coal by the mines of the DTEK company (located in Western Donbas and Dobropilsky district), 23% is the production of PRJSC Pokrovske Colliery (Pokrovsky district), 8% of coal production is provided by mines located in state ownership, and only 4% – other non-state owned mine.

The geological information and mining plans were used to analyse the distribution rate of different strength layers in the floor strata. This information included such data: the lithologia, depth of development and strength of the rocks. In terms of lithology, the Middle Carboniferous formations are mainly composed of sandy-clay rocks. The uniaxial compressive strength (UCS) indicators of rocks are presented in the table 1, where min UCS, max UCS, aver UCS – minimum, maximum and average uniaxial compressive strength respectively, MPa; ΔUCS – mean quadratic value of uniaxial compressive strength respectively, MPa; Δ – coefficient of variation, %.

Table 1. UCS of rocks.

min UCS	max UCS	aver UCS	Δ UCS	Δ, %	Rock type
7.4	57.8	27.8	10.2	36.9	Mudstone
23.4	57.0	32.9	15.3	35.7	Siltstone
41.8	138.6	75.3	25.3	29.5	Sandstone
38.1	193.0	107.0	45.8	42.7	Limestone

The first layer of immediate floor was represented by:

- siltstones in 73% of cases at an average thickness 5.8 m,
- sandstones – 13% at an average thickness 8.3 m,
- mudstones – 9.3% at an average thickness 2.2 m,
- limestones – 4.7% at an average thickness 3.4 m.

The highstrength rocks (with a UCS more than 60 MPa) in the first and second layer of floor strata was observed in 16% of cases with accuracy within the limits of statistical reliability. The analysis indicated that 74% of the coal seams floor was composed by layered siltstones and argillites. Based on the generalization of geological information, a strata histogram was constructed, which characterizes typical conditions for Pokrovsky, Dobropilsky districts and Western Donbass. The strata histogram is illustrated in figure 2.

According to existing ideas, in the absence of water inflows, buckling is the most likely mechanism of floor heave.

3. Methods

The 3D numerical simulation by ANSYS code was performed to analyze the stress-strain distributions in surrounding rock before and after excavation face. This approach made it possible to analyze the evolution of stresses around the roadway in two mutually perpendicular sections (in the longitudinal and cross sections). The simulated rock mass corresponded to the strata histogram presented in figure 2.

To simulate the behavior of rock mass, the Drucker–Prager model was used. Parameters of deformation model such as: Young's modulus, Poisson's ratio, cohesion, angle of internal friction were established in accordance with the methodology proposed by Sakhno, Molodetskyi and Sakhno [23]. Mechanical parameters of rock mass are presented in table 2.

The principle of force superposition was used. The model is axisymmetric, so half of the cross-section of the mine roadway was simulated. The model was 60m long, 60m wide, and 100m high. A 5.2×3.8m arch shape roadway was modeled. The numerical model is shown in figure 3. The load-bearing capacity of the U-shaped steel support (310kN, type KSHPU-17.7) was simulated by applying external pressure to roadway contour.

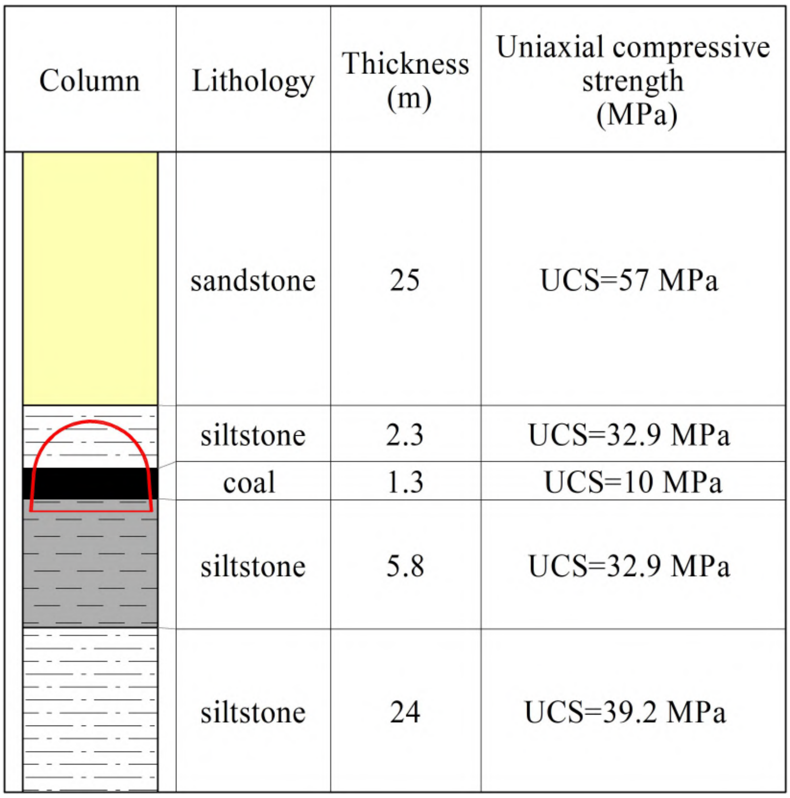


Figure 2. The strata histogram.

The maximum principal stress theory was used as the yield criterion. A vertical pressure of 22.5MPa, that equivalent to overburden stress at a 900m depth, was applied on the top of the model.

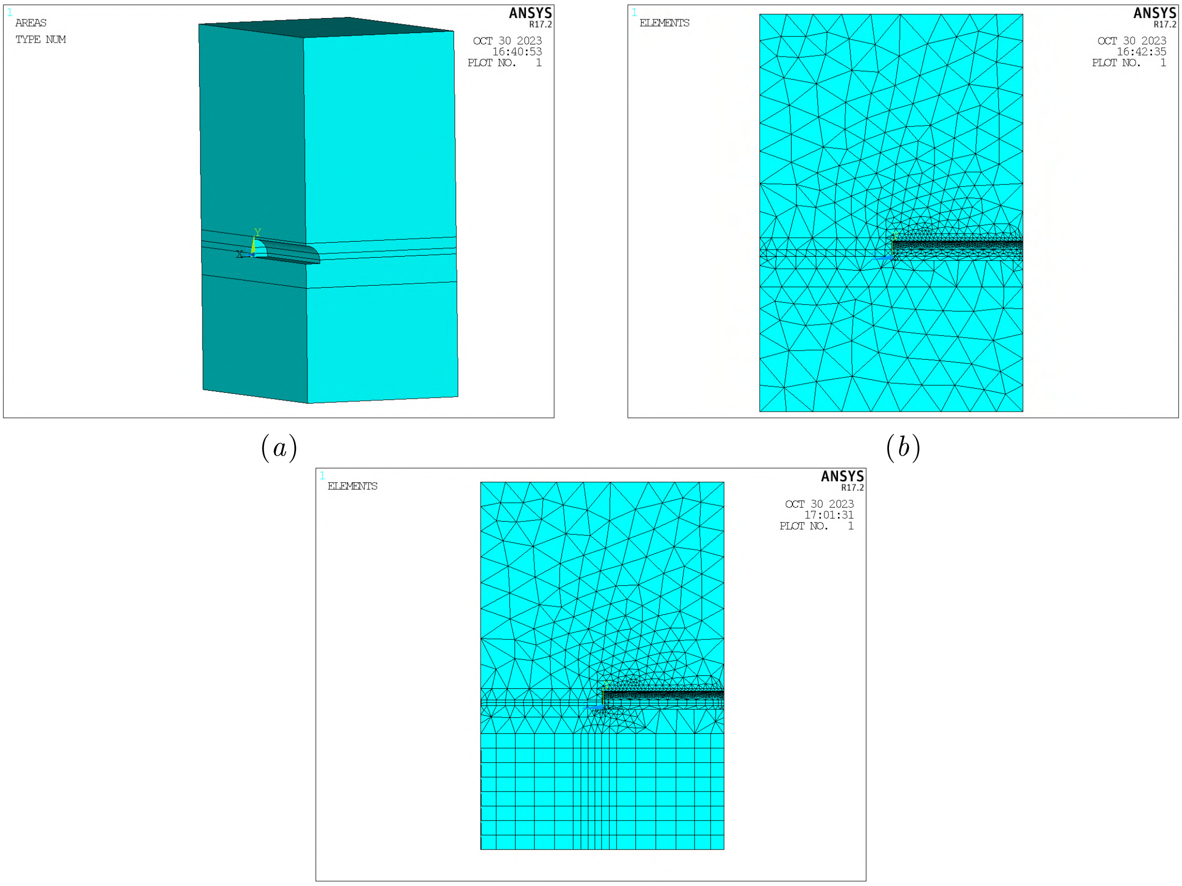
The size of the finite element was refined (figure 3b, c). Near the mine roadway contour, the size of the finite element was minimal, since high accuracy is important there. On the contour of the model the stress field is uniform, so the finite elements size was maximal. This is traditional practice in numerical simulation.

4. Results

The maximum principal stress and strains distributions in the surrounding rock are shown in figure 4.

Table 2. Rock mass parameters for numerical simulation.

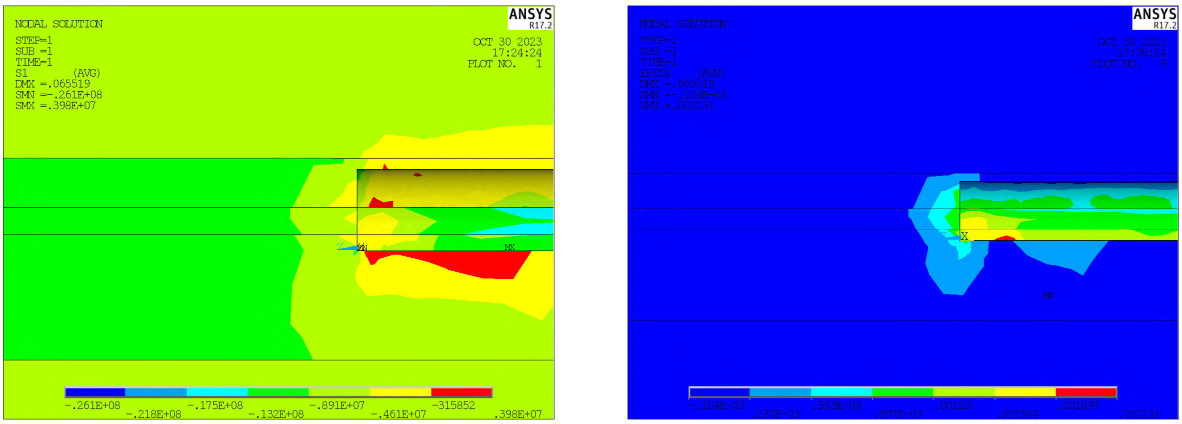
	Density, kg/m^3	Elastic modulus, GPa	Poisson's ratio	Cohesion, MPa	Angle of internal, deg	Dilatancy angle, deg
Main roof	2400	6.12	0.3	5	32	32
Immediate roof	2300	2.20	0.3	6.3	30	30
Coal	1300	1.1	0.25	2.6	26	26
Immediate floor	2300	2.2	0.3	6.3	30	30
Main roof	2300	3,6	0.3	5,35	30	30



(*a*) (*b*)

(*c*)

Figure 3. Numerical simulation model (a), finite element mesh before (b) and after (c) refining.



(*a*) (*b*)

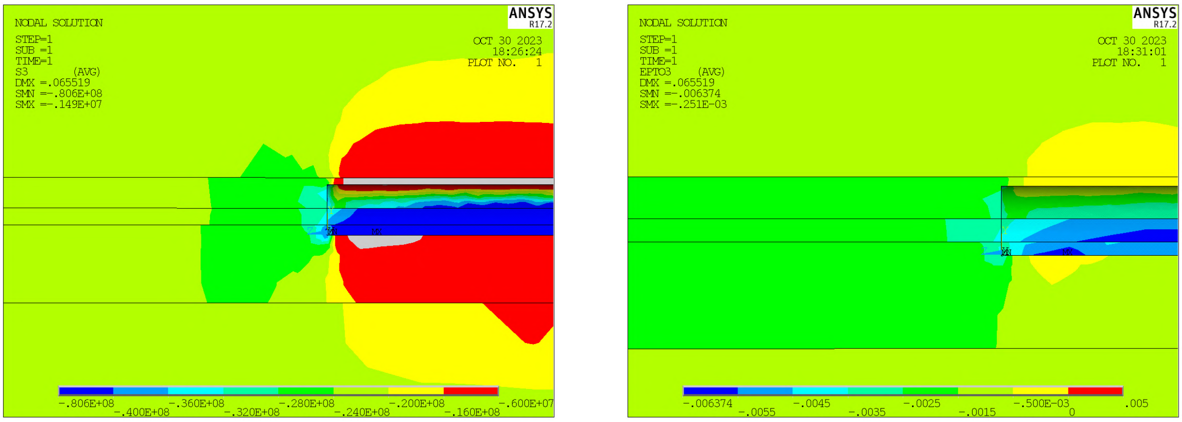
Figure 4. Distributions of maximal principal stresses (a), and maximal principal strains (b) in the surrounding rock.

Analysis of the simulation results (figure 4a) shows that a zone of increased stress is formed before the excavation face, which includes the immediate roof and immediate floor. It is clear, that in this zone, the lithological stresses (determined by gravitation) increase. The rock mass there is compressed. The same conclusion can be drawn from analyzing the strain distribution (figure 4b). At a distance of 1.5-2.0 m from roadway bottom contour, a zone of reduced stresses appears. This zone is marked in red colour in figure 4a. The size and the magnitude of stresses in this zone increase with an increasing of the distance from the excavation face. The maximum tensile stress that occurs in the roadway floor is 3.9 MPa. It exceeds the rock tensile strength.

The minimal principal stress and strains distributions in the surrounding rock are shown in figure 5.

Since the minimal principal stresses are compressive, analyzing the patterns of their distribution, it is possible to estimate the size of stress concentration zone.

This zone is formed before the excavation face. Its maximum depth before face is more than double the height of the roadway. The entire layer of the immediate floor is included into this



(a) (b)

Figure 5. Distributions of minimal principal stresses (a), and maximal principal strains (b) in the surrounding rock.

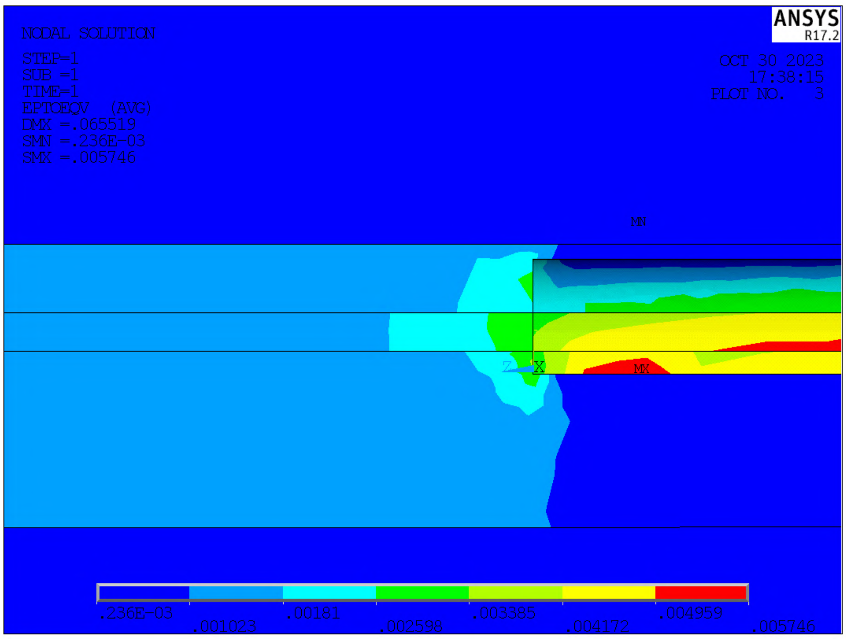


Figure 6. Distributions of equivalent strains in the surrounding rock.

zone. The rocks are compressed there by stresses 25-35 percent higher than the lithological stress. This conclusion is confirmed by the results of minimum principal strain pattern analysis (figure 5b). The zone of reduced stresses is formed in the immediate floor in distance of 1.5-2.0m below the roadway bottom.

The analysis of equivalent strain distribution (figure 6) shows the general characteristic of the deformation state of surrounding rock. In the zone of influence of the excavation face, strain fluctuation is the highest.

A quantitative assessment of stress variation was obtained by analysing of stress graphs along profile lines in immediate floor. As an example figure 7 shows the graph of the minimum principal stresses variation, that was built along a profile line oriented in the immediate floor (0.25m below the bottom) along the roadway axis (figure 7a). The profile line (stress path) is marked with dots in figure 7a. The section 8m before the excavation face and 2.0m behind it is taken into account.

The following conclusions were obtained after analyzing the stress graph (figure 7b):

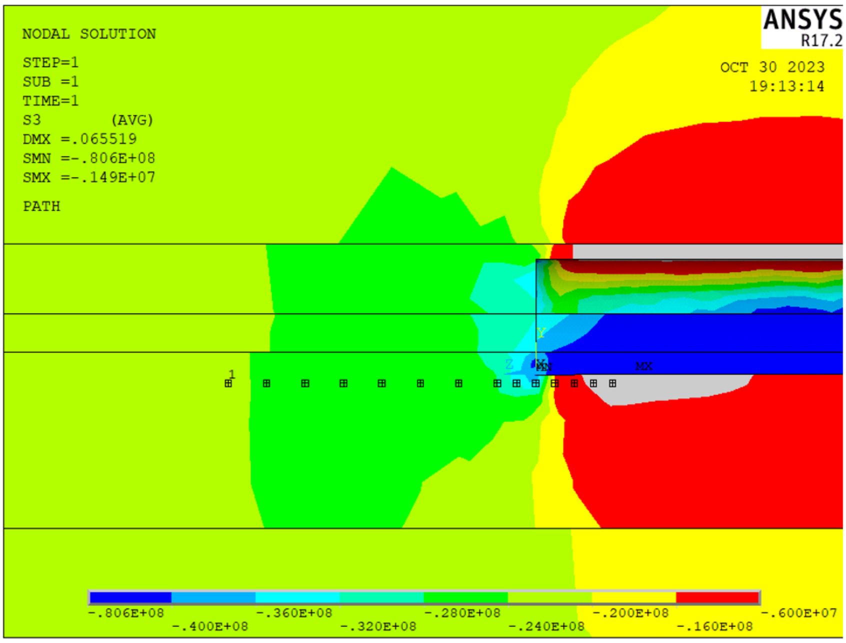
(i) at a distance more than 8 m before the excavation face, the stress field corresponds to the overburden stress (approximately 23.8 MPa);
(ii) the face influence zone begins at a distance of 8.0 m before it. There stress increase from 23.8 to 37.2 MPa, which corresponds to its increase of 56%;
(iii) the stress relief zone in roadway bottom appears immediately under the excavation face surface. There stress decreases rapidly. At a distance of 2.0 m behind the excavation face at a depth of 0.25 m in immediate floor, the stress are 3.8 MPa. Therefore stress reduce rate is 84% relative to the initial stress field and 90% relative to the maximum stress concentration. Thus the rocks in immediate floor are loaded cyclically. At the same time, the sign of the loading-unloading stresses changes.

After that, 4 profile lines were built to analyse stress-strain variation in depth of immediate floor. Profile lines were oriented in the immediate floor along the roadway axis at a distance of 0.25, 0.5, 0.75, 1.0 m from the roadway bottom. The length of the profile lines was 3.0 m before excavation face and 2.0 m after it. figure 8 shows graphs of the minimal principal stresses variation along profile lines. The position of the profile lines is shown in figure 8.

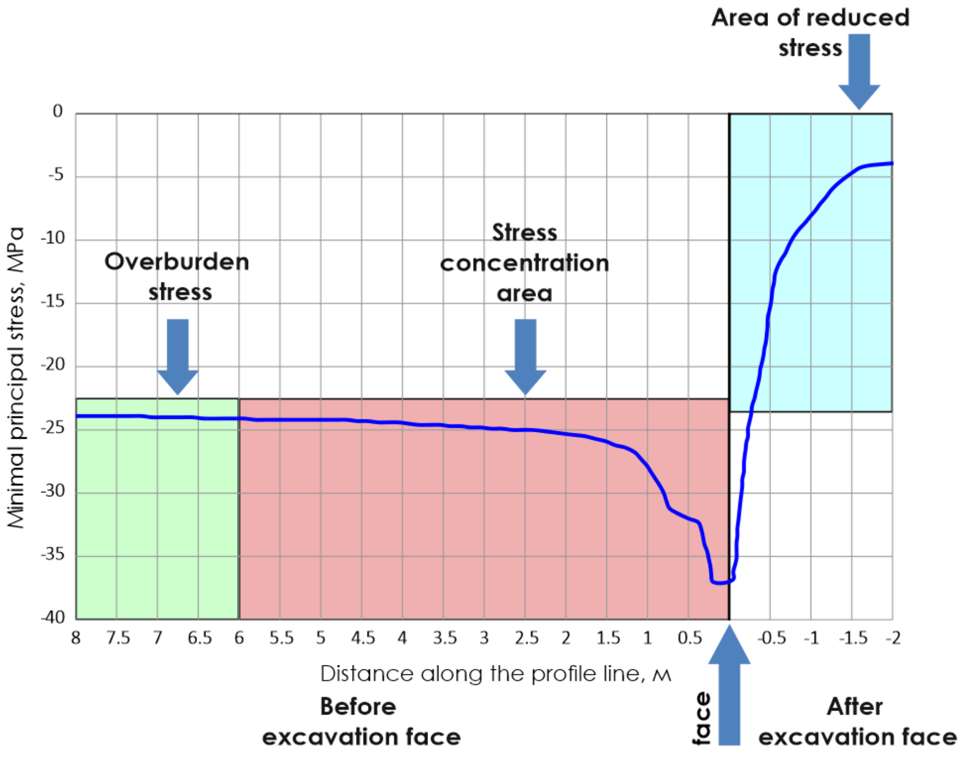
The analysis of the minimal principal stresses variation (figure 8) shows that the stress concentration zone before excavation face in the immediate floor is limited by a depth of 1.0 m. In addition, the magnitude of the stresses before the excavation face decreases with a depth. Similar conclusions can be drawn for the section of immediate floor behind excavation face. The increase of the distance from the roadway bottom leads to a decrease of the stress relief zone. For example, at a depth of 1.0 m from roadway bottom, the stresses in immediate floor at a distance of 2.0 m after excavation face are 7.35 MPa, which corresponds to their decrease of 70%.

Figure 9 shows graphs of the equivalent strain variation along profile lines in the immediate floor along the roadway axis at a distance of 0.25, 0.5, 0.75, 1.0 m from the roadway bottom.

Graphs in figure 9 show changes in the deformation type (compression-tension) in the immediate floor before and after the excavation face. This confirms the stress analysis results. Similar conclusions can be drawn also about the size of the roadway influence zone before and after excavation face. The magnitude and fluctuations of the strain also decrease with depth. For example, at a depth of 0.25 m from roadway bottom, the strain in immediate floor increases by 60% in the stress concentration zone before excavation face and decreases by 87% in the stress relief zone after it. At a depth of 1.0 m, the corresponding percentage are 9%, 77%. The conclusion regarding the sign change of stresses and strains in immediate floor before and after excavation face is confirmed.



(*a*)



(*b*)

Figure 7. Profile line in pattern of minimal principal stresses (a) graph of the minimal principal stresses variation (b).

Thus, it was established that in the immediate floor in the influence zone of excavation face at the initial stage of the roadway life cycle, compressive stresses first increase by more than 50% in the stress concentration zone, after that they decrease by more than 80% in the stress

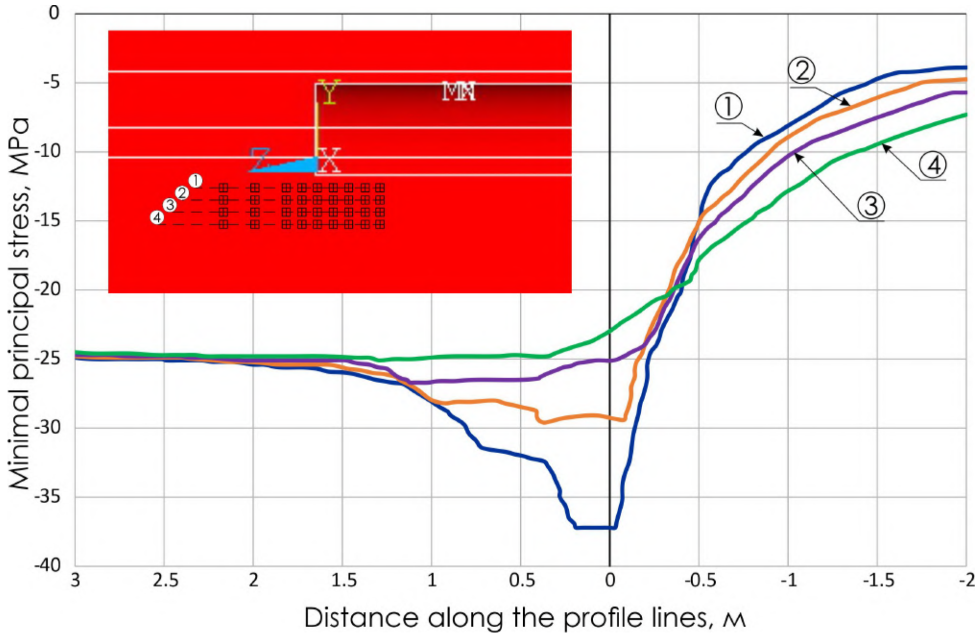


Figure 8. Graphs of the minimal principal stresses variation along profile lines in immediate floor at a distance of: (1) 0.25m, (2) 0.5m, (3) 0.75m, (4) 1.0 m from the roadway bottom respectively.

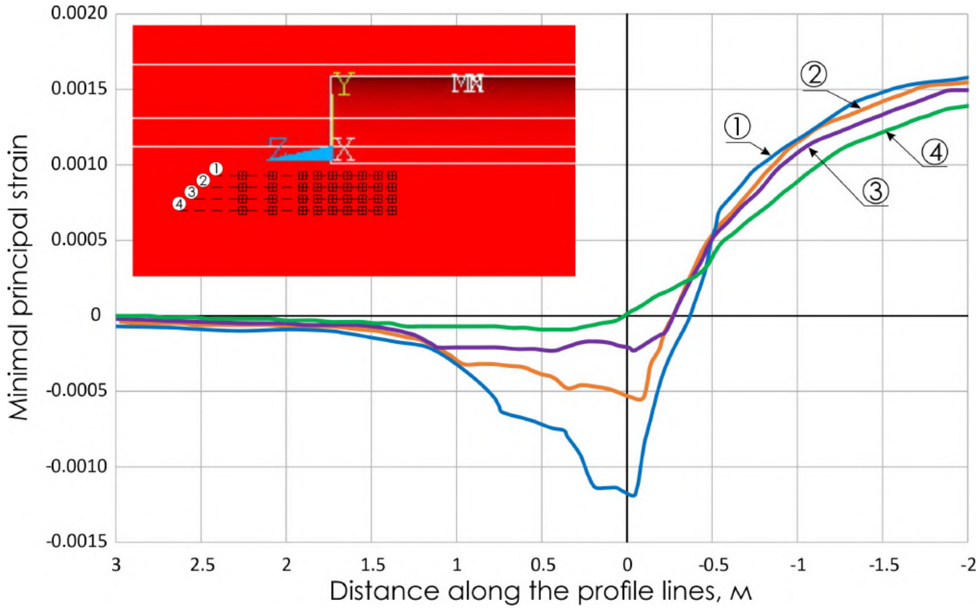


Figure 9. Graphs of the equivalent strain variation along profile lines in immediate floor at a distance of: (1) 0.25m, (2) 0.5m, (3) 0.75m, (4) 1.0 m from the roadway bottom respectively.

relief zone. In this case, the rocks undergo cyclic loading and alternating strains.

5. Discussion

It is known that cyclic loading of rocks leads to a significant decrease in their strength even after the first loading cycle.

Burdine [24], Brown and Hudson [25] first found that cyclically loaded rocks would fail in a limited number of cycles under the condition that the maximum cyclic loading is less than the uniaxial compressive strength of rocks.

Brown and Hudson [25] first illustrated the residual failure locus, and researchers further pointed out that there is a fatigue failure law for rocks. The terminal fatigue strain of rocks is approximately equal to the post-peak monotonic strain [26–28]. In most experiments, the irreversible strain develops a three-stage mode. In the initial stage, the axial strain rapidly develops owing to the closure of pre-existing voids or cracks in rocks. Rocks under cyclic stress usually characterized by low fatigue life.

For soft rocks, the deformation modulus increases during the first few cycles due to closure

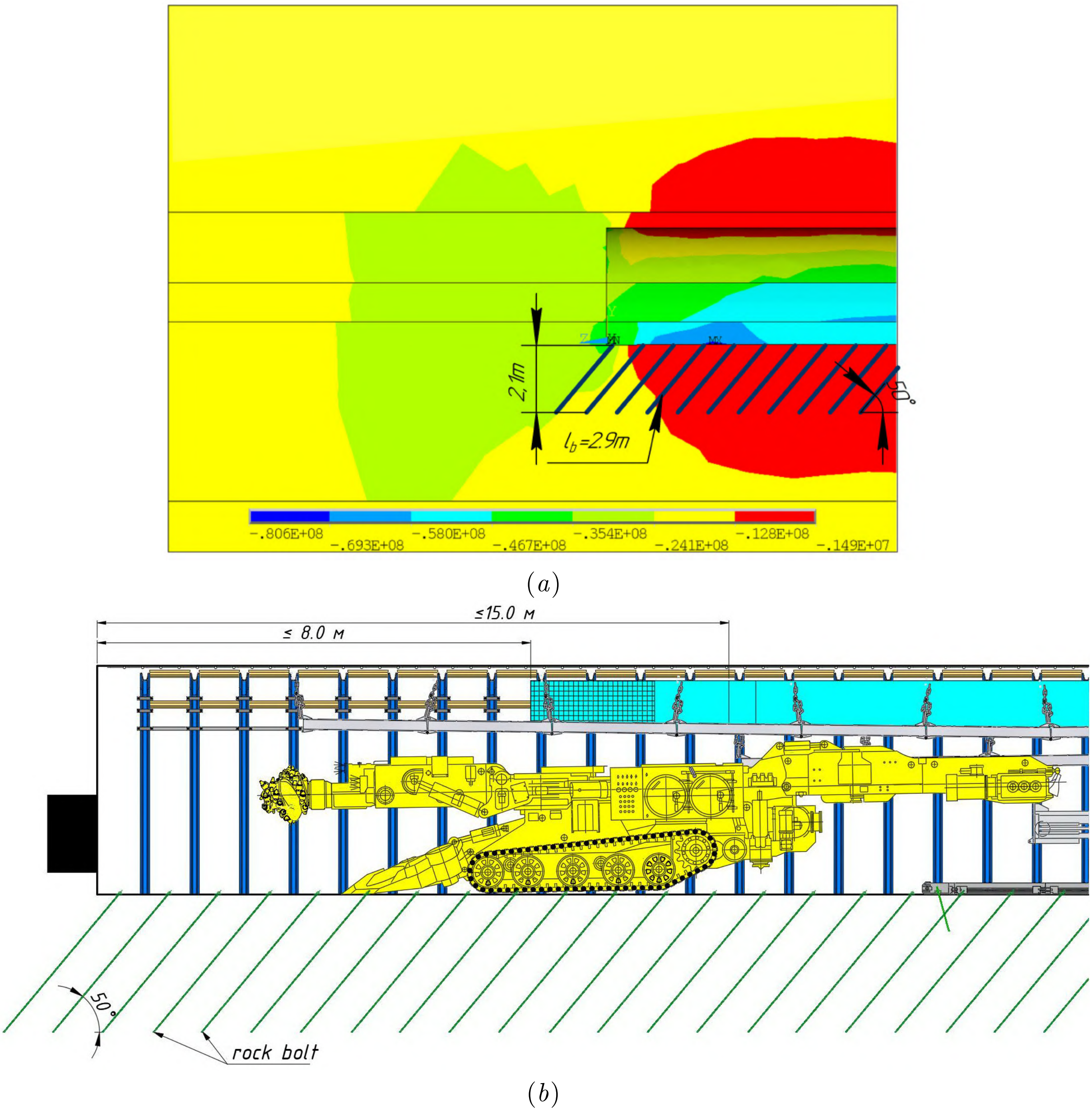


Figure 10. Scheme for determining the rock bolt inclination based on the numerical simulation results (a), floor support scheme during the roadway excavation (b).

of voids and hardening of specimens. For cyclic triaxial compression tests, the irreversible volumetric strain is one of the key quantities related to the dilatancy effects of rocks [29].

Liu and He [30] show that the irreversible volumetric strain is positive in first few cycles and then becomes negative, indicating that the rock specimen is first contracted and then dilated until fatigue failure. The irreversible volumetric strain at the dilatancy point increases with an increasing of confining pressure.

Miao et al. [31] found that cyclic disturbances result to numerous tensile cracks and crack branching. Wang et al. [32] found that the microfracturing processes and accumulation of damage that occurs during cyclic fatigue loading can cause rock failure.

Summarizing the above, it can be concluded that in the immediate floor behind the excavation face in the stress relief zone, cracks are formed in the floor strata and existing structurally defects are branched, interlayer contacts are opened and delamination occurs. This creates a negative impact on the roadway stability in its next life period. In addition it is the origin of floor heave process.

The fracture of rocks can be prevented by artificially restraining the delamination of the immediate floor after excavation face. Rock bolts installed with an inclination to roadway face were proposed for this. However, this method will be effective only if the bolts are installed in a timely manner rapidly in the excavation face. Thus, the rocks will be reinforced in the stress concentration zone, and their subsequent delamination in the stress relief zone will be controlled by rock bolts.

The rock bolt inclination is advisable to determine from the stress pattern in immediate floor. The most appropriate bolt inclination coincides with the contour of the stress concentration zone. Research on the optimal support scheme and floor reinforcement length for rock bolts is proposed by Sakhno and Sakhno [16]. The example of determining the bolt inclination by a graphical method for the simulation results presented above is shown in figure 10a. The proposed technology of mine roadway excavation and floor support is presented in figure 10b. The figure shows rock bolts with standard length of 2.9 m used in Ukrainian mines.

6. Conclusions

This paper presents the numerical simulation results of underground roadway excavation impact on the origin floor heave. In this study, deep mining roadway of coal mines located in Pokrovsky, Dobropilsky districts and Western Donbass was considered as the research subject. Based on the results of this investigation, the following conclusions can be drawn:

1. The numerical analysis shows that in immediate floor before roadway's excavation face a zone of increased stress is formed. Maximal comressive stress in this zone increases the lithological stress by more then 50%. The stress relief zone in immediate floor after excavation face appears. The stress there is less than the lithological stress and maximum stress by more than 80% and 90% respectively. Thus the rocks in immediate floor are loaded cyclically. This is confirmed by alternating strains in the area of face excavation impact.
2. An analysis of the literature indicates that cyclically loaded rocks would fail in a limited number of cycles under the condition that the maximum cyclic loading is less than the uniaxial compressive strength of rocks. Thus, in the immediate floor behind the excavation face cracks are formed and structurally defects are branched. This creates a negative impact on the roadway stability and origin of floor heave process.
3. Rock bolts support of roadway floor was proposed for restraining the delamination of the immediate floor after excavation face. In this case, bolts installation in a timely manner in the excavation face with inclination to roadway face was proposed. The most appropriate bolt inclination coincides with the contour of the stress concentration zone. Further research

will be aimed at studying the influence of rock bolts installed immediately in the roadway face on the stress-strain evolution in the roadway floor.

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Predictive calculation of blasting quality as a tool for estimation of production cost and investment attractiveness of a mineral deposit development

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Abstract. This study delves into the importance of ensuring the necessary degree of rock crushing in open pit mining technology and its profound impact on extraction, loading operations, and overall production processes. The degree of rock crushing significantly influences excavation and transportation costs, making it a pivotal factor in determining the total cost of mining operations. Traditionally, empirical formulas have been used to establish the dependence of granulometric composition of blasted rocks on rock properties and technological factors. However, this study emphasizes the need for a multifactorial model to predict rock crushing quality, incorporating characteristics of rock massifs, explosives, and specific costs. By doing so, it aims to enhance the efficiency of open-pit mining technology and evaluate the investment attractiveness of deposit development at the pre-project stage. The study also explores the use of linear regression analysis and non-linear search methods to determine the parameters for predictive calculations of blasting quality. The research offers valuable insights into optimizing blasting approaches and minimizing operational costs in open-cast mining operations, thereby contributing to the sustainable development of mineral deposits.

1. Introduction

Ensuring the required degree of crushing of rocks is one of the main problems in open pit mining technology. The necessary degree of crushing has a significant effect on the extraction and loading operations, and accordingly on all technological processes in the open pit. If rock crushing is of insufficient quality, the content of oversized pieces increases, the excavation process is complicated, the duration of non-productive time spent on selecting and removing oversized pieces increases, and the costs of transportation and mechanical crushing increase. This leads to a decrease in the productivity of the extraction and loading and transport equipment, increases their downtime during the shift, as well as the costs of repair and maintenance of excavators.

In this regard, the definition of piecemealness is of great importance, since this information is a tool that allows to connect all production processes, to balance them in the direction of minimizing the total cost.

Until recently, there was no alternative to the empirical formulas. These formulas very roughly established the dependence of the granulometric composition of the blasted rocks on the physical properties of the rocks and technological factors.

The study of the influence of various natural and technological factors on the size of the average piece of the blasted rock mass, and therefore on the intensity of crushing, is relevant today. An important factor is establishing the dependence of the granulometric composition of the blasted mining rocks on the physical properties of the rocks and explosives.

Therefore, in order to further improve the efficiency of open-pit mining technology, it is necessary to solve the urgent task of creating a multifactorial model for determining the quality of rock crushing, for example, in the form of the size of the average piece from the characteristics of the massif of rocks, used explosives and their specific costs. And, accordingly, determining the quality of future rock crushing is an important factor for aggregated forecasting of the cost of mining operations. In turn, the solution of this task will help to evaluate the investment attractiveness of deposit development at the pre-project stage.

2. Literature review

Formulas for calculating the parameters of the location of charges from the properties of the mass of rocks and explosives prevail in the literature [1–3]. Leng et al. [4] proposes to carry out drilling and blasting works according to a checkerboard scheme of commutation of charges with a combination of wells with a diameter of 138 and 200 mm, which will ensure the proper quality of rock crushing, provided that the specific consumption of explosives is constant.

Dhekne, Pradhan and Jade [5] describe a method of modeling artificial neural networks for predicting the number of oversized pieces formed as a result of blasting wells of different diameters. It was established that the decrease in the number of oversizes occurred due to the increase in the diameter of the well.

Li et al. [6] consider the problems of low explosion energy utilization rate due to the use of inappropriate blasting materials during blasting. The method of development and testing of a self-inflating material is presented. As a result of field tests, it was established that the quality of rock crushing using a self-inflating hammer improves compared to a hammer made of drill bits.

Based on the Kuz-Ram model, a simulator for predicting rock crushing quality using the Monte-Carlo method was developed by Morin and Ficarazzo [7]. This tool allows you to predict the outcome of blasting, taking into account various factors, such as the properties of rocks and explosives, as well as blasting patterns. The authors believe that the use of Monte-Carlo simulation will improve the efficiency of blasting operations and optimize the economic performance of open-pit mining operations.

In the paper [8], research was carried out on the optimization of blasting parameters using a deep neural network. A model was created for the conditions of the Skhidniy open-pit to establish the relationship between blasting parameters and rock fragmentation and their forecasting. It was established that the neural network, optimized with the help of a genetic algorithm and numerical simulation, has the highest accuracy in predicting the result of blasting operations.

Most textbooks, reference books and articles are dominated by formulas for calculating the parameters of the location of charges from the properties of the mass of rocks and explosives [5,9,10]. At the same time, it is believed that a rational grinding quality will be achieved [11–13], but specific indicators of this quality are not given. There are not enough mathematical formulas in which the characteristics of rocks, explosives and the result of the explosion would be connected at the same time. In works [14,15] the mathematical formula (1) of V. A. Kuznetsov is proposed:

$$d_c = 0.1 \times \left(\frac{(d_e \times \gamma)^{0.5} \times (f \times d)^{0.33}}{q} \right) \le d_e \tag{1}$$

where f is the strength coefficient of rocks according to M. M. Protodeaconov; d_e – the average block size in the array, m; γ – volumetric weight of the rock, t/m^3; d – charge diameter, m; q – specific consumption of explosives, kg/m^3;

Taking into account the specific characteristics of explosives could increase the accuracy of this calculation approach, but their use is not envisaged here.

If we analyze the factor characteristics in the formula of V. A. Kuznetsov, we rightly note that the most influential of them is the specific consumption of explosive, since it is in the first degree. Other factors have a degree much less than one and are mainly the properties of rocks, and even the diameter of the blast hole. There are no properties of explosive, which is probably explained by the fact that the creation of the formula was preceded by many years of work in the conditions of the use of granular explosive, and the accumulated material served as an irreplaceable foundation for this mathematical expression. Attempts to use the given formula in practice show that it is valid for super-strong hard-rock rocks. It should be noted that the formula serves as the basis for creating a classification of explosiveness in the form of a mathematical expression, the main product of which is the size of the average piece, and the detailing is not strictly limited to categories [16–19]. In addition, it can be adapted to the conditions of any specific production and, thus, unlike previously created classifications, it gives a specific answer for deterministic work conditions [20].

Perehudov [21] obtained an empirical formula for calculating the size of the average piece in the blasted rock depending on the specific consumption of the explosive substance q, the volume of the rock detonated by one blast hole charge Q and the strength of the rock f:

$$d_{av} = \beta \times \left(\frac{Q^{1-a}}{q^a}\right) \times \sqrt{\frac{f}{\rho}}, \tag{2}$$

where a, β are empirical coefficients.

Taking into account dependence (2), Perehudov [21] obtained an analytical expression for determining the rational value of the specific consumption of explosive in the following form:

$$q = \beta \times \left(\sqrt{\frac{100 \times f}{\rho}} \times \frac{Q^{1-a}}{d_{av}}\right)^{\frac{1}{a}}. \tag{3}$$

This expression was obtained for the mining and geological conditions of the Pershotravnevy and Hannivsky open-pits of PJSC "Northern Mining and Processing Plant".

Let's consider the peculiarities of the impact on the quality of rock crushing of cracking indicators and physical and mechanical properties of rocks [3, 4, 8, 22].

The influence of fracturing as the main factor in the explosive destruction of a massif of rocks was studied by Yuanjuan [23], Johansson [24], Esen et al. [25]. The results of their research showed, that in general this influence manifests itself in two ways. For this reason, fracturing largely determines, especially in the zone of poorly regulated crushing, the chunkiness and shape of the pieces of the blasted mining mass [26].

V. K. Rubtsov was one of the first who use the blockiness value of the massif to estimate its explosiveness [27]. He also additionally proposed to evaluate the fracturing (explosiveness) of the massif by the content of large fractions in it (0.3, 0.7 and 1.0 m).

However, this characteristic is essentially superfluous, since the fractional composition and the average size of individual units in rock massifs are functionally related. This is confirmed by the research by Wang and Konietzky [28], who showed that the average diameter of individual particles calculated from the fractional composition of individual particles determined as a result of field measurements in the massif coincides with the value of the average distance between cracks.

Based on the results of research by V. K. Rubtsov, a unified classification of rocks by the degree of fracture of rocks for open-pits was developed [27]. It includes 5 categories of rocks that differ in the average diameter of individuals: I – up to 0.1; II – 0.1-0.5; III – 0.5-1.0; IV – 1.0-1.5; V – more than 1.5 m.

A number of laboratory studies, as well as the experience of blasting work in open-pits, determined that maximum crushing of rocks and a flat surface of the slopes are achieved in the case when the chipping is carried out perpendicular to the main system of steeply and subvertically falling cracks (usually layered), that is, perpendicular to the long edge individualities [29]. The most unfavorable situation is when the blasting is carried out at an angle of 45° to the main system of such cracks, while along with the unsatisfactory crushing of the rocks, cuts are formed in the back of the massif along the cracks. Also, horizontal arrangement of cracks of the main system, perpendicular to the axis of blast hole charges, is unfavorable from the point of view of the quality of explosive destruction of the massif [30].

Thus, when carrying out in-situ studies of rock fissures in quarries for the purpose of studying their explosiveness, it is necessary to document the orientation of the cracks, the size and shape of individual parts. The main indicator of fissuring, which is included in the absolute majority of formulas for calculating the specific consumption of explosives and by which classes (categories) of rocks are distinguished by fissuring, is the average size of the elementary structural block (natural separation).

To solve the question of the influence of various factors and characteristics of explosives on the diameter of the average piece in the blasted mining rocks, it is necessary to perform a statistical analysis of experimental data, which will allow obtaining mathematical relationships between these factors and the quality of crushing.

3. Results

In the blasted rock mass after the explosion, pieces of different sizes are formed. The analysis of the results of the explosions indicate that there is a correlation between the sizes of rock pieces after the explosion, the properties of the rock mass and the explosives used for the explosions. Analytically, such a dependence can be written in the form:

$$\bar{d} = f(\bar{D}, f, q, Q, \Delta), \tag{4}$$

where $\bar{d}$ – average size of rock pieces after the explosion, m; $\bar{D}$ – the average size of the block in the rock massif, m; f – rock strength coefficient according to M.M. Protodiakonov; q – specific consumption of explosives, kg/m^3; Q – explosion energy of explosives, kJ/kg; Δ – charging density, kg/m^3.

At the first step of finding dependence (4), we select its structure. Taking into account the characteristics of the explosion and the results of the experiments, we conclude that it is appropriate to choose the structure of formula (4) in multiplicative form:

$$\bar{d} = K \times \bar{D}^{a_1} \times q^{a_2} \times Q^{a_3} \times \Delta^{a_4}, \tag{5}$$

where $K = a + b \times f$; a, b, a_i $(i = 1, \ldots, 4)$ – numerical parameters.

At the second step of finding the dependence (4), we will find the values of the parameters, a, b, a_i $(i = 1, \ldots, 5)$ according to the results of experiments.

First, to simplify the analysis of the obtained results, it is natural to reduce formula (4) to a dimensionless form:

$$d = K \times D^{a_1} \times q^{a_2} \times Q^{a_3} \times \Delta^{a_4}, \tag{6}$$

where $d = \frac{\bar{d}}{d_0}$, $D = \frac{\bar{D}}{D_0}$, $f = \frac{f}{f_0}$, $q = \frac{q}{q_0}$, $Q = \frac{Q}{Q_0}$, $\Delta = \frac{\Delta}{\Delta_0}, K = a \times (1 + c \times f)$, $c = \frac{b}{a}$.

Value $d_0, D_0, f_0, q_0, Q_0, \Delta_0$ can be called basic, have meaningful units of measurement, and are determined by analyzing the statistical results of experiments. To facilitate finding parameter values a, b, a_i $(i = 1, \ldots, 5)$ prologarithm (3), which will give:

$$\ln d = \ln(1 + c \times f) + \ln a + a_1 \ln D + a_2 \ln q + a_3 \ln Q + a_4 \ln \Delta, \tag{7}$$

Taking into account the peculiarities of the occurrence of parameters in (7) for the purpose of applying linear regression analysis, it is advisable to transform (7) into the form:

$$y = a_0 + \sum_{i=1}^{4} a_i \cdot x_i, \tag{8}$$

where $y = \ln\left(\frac{d}{1+c\times f}\right)$, $a_0 = \ln a$, $x_1 = \ln D$, $x_2 = \ln q$, $x_3 = \ln Q$, $x_4 = \ln \Delta$.

Parameters $a, a_i (i = 1, \ldots, 5)$ we will find with the help of linear regression analysis, but to find the value of c, and, therefore, b, it is necessary to use non-linear search methods. In the future, we add the sum of the squares of the deviations of the values obtained as a result of experiments from those calculated according to formula (8) and get:

$$F(a_0, a_1, a_2, a_3, a_4, c) = \sum_{k=1}^{n} \left(y_k - a_0 - \sum_{i=1}^{4} a_i \cdot x_{ik} \right)^2, \tag{9}$$

where $y_k = \ln\left(\frac{d_k}{1+c\times f_k}\right)$, $x_{1k} = \ln D_k$, $x_{2k} = \ln q_k$, $x_{3k} = \ln Q_k$, $x_{4k} = \ln \Delta_k$, $d_k = \frac{\bar{d}_k}{d_0}$, $D_k = \frac{\bar{D}_k}{D_0}$, $f_k = \frac{\bar{f}_k}{f_0}$, $q_k = \frac{\bar{q}_k}{q_0}$, $Q_k = \frac{\bar{Q}_k}{Q_0}$, $\Delta_k = \frac{\bar{\Delta}_k}{\Delta_0}$.

Thus, the task of finding parameter values is reduced to the minimization of function (7).

$$F(a_0, a_1, a_2, a_3, a_4, c) \to \min_{a_0, a_1, a_2, a_3, a_4, c}. \tag{10}$$

Taking into account the structure of function (10), the algorithm of conditional minimization of this function is implemented, taking into account the parameter c according to the parameters $a_i (i = 0, \ldots, 4)$. The parameter c is chosen in such a way as to minimize (9), but with explosives hiding the physical meaning of the parameters being sought. We emphasize that the parameters $a_i (i = 1, \ldots, 4)$ indicate the rate of relative change in the average size of a piece of rock $\bar{d}$ from the relative change of values $\bar{D}, q, Q$ and Δ, respectively. Indeed, calculating the partial derivatives, we have:

$$\frac{\partial \bar{d}}{\partial \bar{D}} \times \frac{\bar{D}}{\bar{d}} = a_1, \quad \frac{\partial \bar{d}}{\partial q} \times \frac{q}{\bar{d}} = a_2, \quad \frac{\partial \bar{d}}{\partial Q} \times \frac{Q}{\bar{d}} = a_3, \quad \frac{\partial \bar{d}}{\partial \Delta} \times \frac{\Delta}{\bar{d}} = a_4. \tag{11}$$

At the same time, the rate of relative change in the average size of a piece of rock $\bar{d}$ from the relative change in size f has a more complex form, which is caused by the requirement of physical content, and is calculated by the formula:

$$\frac{\partial \bar{d}}{\partial f} \times \frac{f}{\bar{d}} = \frac{c \times f}{1 + c \times f}. \tag{12}$$

Expressions (11) and (12) make it possible to determine the limits on these values, which would correspond to the physical content of the found parameters.

Parameters found $c, a_i (i = 0, \ldots, 4)$ we will check their significance using statistical methods, in particular, testing the hypothesis that they are not equal to zero. For this, we will use the Student distribution. First, we calculate the parameter statistics a_i:

$$t_i = \frac{|a_i|}{s_{a_i}}, \tag{13}$$

where s_{a_i} – the standard deviation of the parameter a_i.

Next, according to the selected level of significance α and the number of degrees of freedom k according to the Student's distribution table, we find $t_{\alpha,k}$. If $t_i \geq t_{\alpha,k}$ is fulfilled, it is considered to be at the level of significance α that the parameter is $a_i \neq 0$. To check the adequacy of the found formula to the results of the experiments, we will use dispersion analysis, for which we will check the significance of the multiple correlation coefficient using the Fisher test, calculating statistics:

$$F = \frac{(n-l-1)}{l} \times \frac{r^2_{y.x_1x_2\ldots x_l}}{1 - r^2_{y.x_1x_2\ldots x_l}}, \tag{14}$$

where n – sample size, l – number of independent variables, $r_{y.x_1x_2\ldots x_l}$ – multiple correlation coefficient.

Next, according to the Fisher distribution table for the selected level of significance α, we find the value $F_\alpha(l, n-l-1)$. If there is an inequality $F > F_\alpha(l, n-l-1)$, then with probability $1-\alpha$ it can be stated that there is a dependence between y and variables $x_1, x_2, \ldots, x_l$. The results of series of experimental explosions in open-pits are summarized in table 1.

Table 1. The results of experimental explosions on the study of the size of pieces of rock from the properties of the rock mass and explosives.

№	d, m	D, m	f	q, kg/m^3	Q, kJ/kg	Δ, kg/m^3
1	0.04	0.05	2	0.278	3220	1210
2	0.049	0.07	3	0.376	3000	1250
3	0.039	0.09	4	0.467	4316	950
4	0.055	0.1	5	0.552	3220	1210
5	0.089	0.2	6	0.633	3000	1250
6	0.082	0.3	7	0.711	4316	950
7	0.131	0.4	8	0.786	3220	1210
8	0.162	0.5	9	0.858	3000	1250
9	0.13	0.6	10	0.929	4316	950
10	0.192	0.7	11	0.998	3220	1210
11	0.225	0.8	12	1.065	3000	1250
12	0.175	0.9	13	1.131	4316	950
13	0.25	1	14	1.195	3220	1210
14	0.287	1.1	15	1.259	3000	1250
15	0.218	1.2	16	1.321	4316	950
16	0.308	1.3	17	1.383	3220	1210
17	0.347	1.4	18	1.443	3000	1250
18	0.261	1.5	19	1.503	4316	950
19	0.364	1.6	20	1.562	3220	1210

Table 2 summarizes the coded values of the results of the experiments according to formula (6). We present the basic values of the quantities according to one of the experiments: $d_0 = 0.25$ m, $D_0 = 1$ m, $f_0 = 14$, $q_0 = 1.195\,\text{kg/m}^3$, $Q_0 = 3220\,\text{kJ/kg}$, $\Delta_0 = 1210\,\text{kg/m}^3$.

After logarithmizing the coded results of experiments on the size of rock pieces from the properties of the rock mass and explosives, we get an array of numbers for statistical processing of which it is advisable to use the "LINEAR" function, which is part of the "Function Master" of the Microsoft Excel program. The results of such calculations are shown in table 3. The last column of table 3 shows the values of the final error when the experimental results are approximated by the function (8).

Table 2. Encoded results of experiments on the study of the size of pieces of rock from the properties of the rock mass and explosives.

№	d	D	f	q	Q	Δ
1	0.16	0.05	0.142857	0.232636	1	1
2	0.196	0.07	0.214286	0.314644	0.931677	1.033058
3	0.156	0.09	0.285714	0.390795	1.340373	0.785124
4	0.22	0.1	0.357143	0.461925	1	1
5	0.356	0.2	0.428571	0.529707	0.931677	1.033058
6	0.328	0.3	0.5	0.594979	1.340373	0.785124
7	0.524	0.4	0.571429	0.657741	1	1
8	0.648	0.5	0.642857	0.717992	0.931677	1.033058
9	0.52	0.6	0.714286	0.777406	1.340373	0.785124
10	0.768	0.7	0.785714	0.835146	1	1
11	0.9	0.8	0.857143	0.891213	0.931677	1.033058
12	0.7	0.9	0.928571	0.946444	1.340373	0.785124
13	1	1	1	1	1	1
14	1.148	1.1	1.071429	1.053556	0.931677	1.033058
15	0.872	1.2	1.142857	1.105439	1.340373	0.785124
16	1.232	1.3	1.214286	1.157322	1	1
17	1.388	1.4	1.285714	1.207531	0.931677	1.033058
18	1.044	1.5	1.357143	1.257741	1.340373	0.785124
19	1.456	1.6	1.428571	1.307113	1	1

Table 3. Results of finding the minimum of function (6) by parameter c.

c	a_0	a_1	a_2	a_3	a_4	S_{fin}
0.7	-0.526	0.658	-0.344	-0.645	0.392	$1.28 \cdot 10^{-3}$
0.8	-0.585	0.661	-0.409	-0.661	0.369	$9.23 \cdot 10^{-4}$
0.9	-0.643	0.657	-0.453	-0.724	0.288	$8.90 \cdot 10^{-4}$
1	-0.692	0.662	-0.489	-0.687	0.334	$9.30 \cdot 10^{-4}$
1.1	-0.742	0.662	-0.513	-0.697	0.32	$1.06 \cdot 10^{-3}$
1.2	-0.789	0.661	-0.528	-0.706	0.308	$1.19 \cdot 10^{-3}$

The analysis of table 3 allows us to conclude that the optimal value is the $c_{\text{opt}} = 0.9$. Thus, the optimal values of the parameters have been established: $a_0 = -0.643$, $a_1 = 0.657$, $a_2 = -0.453$, $a_3 = -0.724$, $a_4 = 0.288$, $c = 0.9$.

To check the significance of the found parameters, we will use the Student's criterion. According to the calculations, the standard deviations for the found parameter values are as follows: $s_{a_0} = 0.002038$, $s_{a_1} = 0.00696$, $s_{a_2} = 0.0148$, $s_{a_3} = 0.0876$, $s_{a_4} = 0.112$.

We calculate the value of statistics according to formula (12): $t_0 = \frac{|a_0|}{s_{a_0}} = \frac{0.0643}{0.002038} = 31.55$, $t_1 = \frac{|a_1|}{s_{a_1}} = \frac{0.657}{0.00696} = 94.4$, $t_2 = \frac{|a_2|}{s_{a_2}} = \frac{0.453}{0.0148} = 30.61$, $t_3 = \frac{|a_3|}{s_{a_3}} = \frac{0.724}{0.0876} = 8.26$, $t_4 = \frac{|a_4|}{s_{a_4}} = \frac{0.288}{0.112} = 2.57$.

Using the Student's distribution table, we find the critical value for the level of significance $\alpha = 0.01$ and the number of degrees of freedom $k = 25$, $t_{0.01;25} = 2.787$. Given that $t_i > t_{0.01;25}$

Table 4. Calculation of the average size of a piece in the crushed rocks mass by an explosion depending on the specific consumption of the explosive substance.

f	D_{av}, m	$0.8q$	$0.9q$	q	$1.1q$	$1.2q$	$0.8d_{\text{av}}$	$0.9d_{\text{av}}$	d_{av}	$1.1d_{\text{av}}$	$1.2d_{\text{av}}$
6	0.2	0.51	0.57	0.63	0.69	0.75	0.06	0.06	0.05	0.04	0.04
8	0.4	0.62	0.71	0.78	0.85	0.93	0.11	0.1	0.09	0.08	0.07
10	0.6	0.74	0.84	0.93	1.02	1.11	0.15	0.13	0.12	0.11	0.1
12	0.8	0.85	0.95	1.06	1.16	1.27	0.19	0.17	0.15	0.14	0.13
14	1.0	0.95	1.07	1.19	1.30	1.42	0.23	0.21	0.19	0.17	0.15
16	1.2	1.06	1.18	1.32	1.45	1.58	0.27	0.24	0.22	0.20	0.18
18	1.4	1.15	1.29	1.44	1.58	1.72	0.32	0.28	0.25	0.23	0.21
20	1.6	1.25	1.40	1.56	1.71	1.87	0.36	0.32	0.28	0.26	0.24

($i = 0, \ldots, 4$), we conclude that the found values of the parameters are significant at the level of $\alpha = 0.01$.

Adequacy of the found formula to the results of experiments is checked by the significance of the multiple correlation coefficient using the Fisher test. We calculate statistics according to formula (13), using the result of calculating the multiple correlation coefficient $r^2_{y.x_1x_2\ldots x_5} = 0.999$.

Using the Fisher distribution table with equal significance $\alpha = 0.01$ and the number of degrees of freedom $k_1 = 6$ and $k_1 = 24$, we find $F_{0.01}(6, 24) = 3.67$. Considering that $F > F_{0.01}(6, 24)$, we conclude that with probability $1 - \alpha = 0.99$ there is a dependence between y and variables $x_1, x_2, \ldots, x_5$.

Thus, formula (6) takes the form:

$$\frac{\bar{d}}{0.25} = (0.526 + 0.473 \times f) \times \left(\frac{\bar{D}}{1}\right)^{0.657} \times \left(\frac{q}{1.195}\right)^{-0.453} \times \left(\frac{Q}{3220}\right)^{-0.724} \times \left(\frac{\Delta}{1210}\right)^{0.288} \tag{15}$$

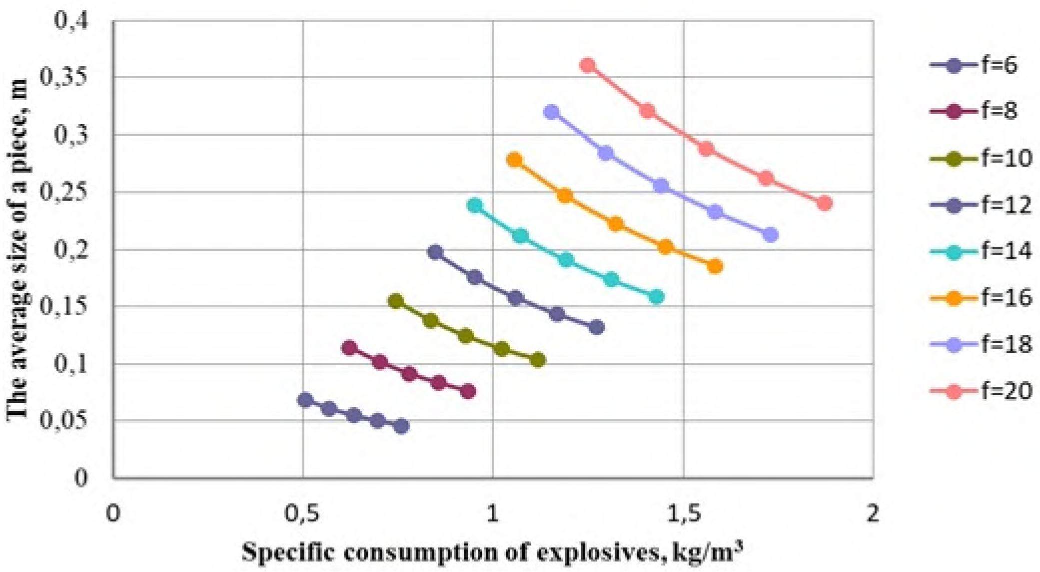

Figure 1. Graphs of the dependence of the size of the average piece on the specific consumption of explosives.

This formula makes it possible to obtain dependences of the size of the average piece in a specific rock that is in the classification [31] or between the boundaries of its categories.

Let's calculate the value of the size of the average piece for rocks with different strength f according to the scale of M. M. Protodyakonov, based on the above-mentioned classification of rocks by blasting in table 4. As one of the main factors, we take the specific consumption of the explosive substance. We take the explosion energy Q and charge density Δ as 3220 kJ/kg and 1210 kg/m^3 (anemix-70), respectively. The average distance between the cracks D_{av} is taken according to the classification. Let's calculate its value by 20 and 10% in the direction of growth and 10 and 20% in the direction of decrease from the reference value of the specific consumption given in the classification.

In figure 1 shows the dependence of the average piece size on the specific consumption of explosives for different rock strengths, which makes it possible to predict the quality of rock crushing at the design stage of mass explosions in open-pits with different properties.

On the basis of the classification of rocks by blasting, we will establish the dependence of the expected size of the average piece in the collapse on the blockiness of the massif. To do this, we

Table 5. Dependence of the expected size of the average piece in the collapse on the blockiness of the massif.

D_{av}, m	0.1	0.1	0.1	0.5	0.15	0.75	0.2	1.0	0.25	1.25	0.3
d_{av}, m	0.015	0.022	0.028	0.043	0.075	0.113	0.117	0.176	0.158	0.238	0.199
D_{av}, m	1.5	0.5	1.7	0.75	1.8	0.8	1.9	1.0	2.0	1.5	1.5
d_{cep}, M	0.299	0.24	0.361	0.281	0.422	0.323	0.485	0.364	0.547	0.406	0.609

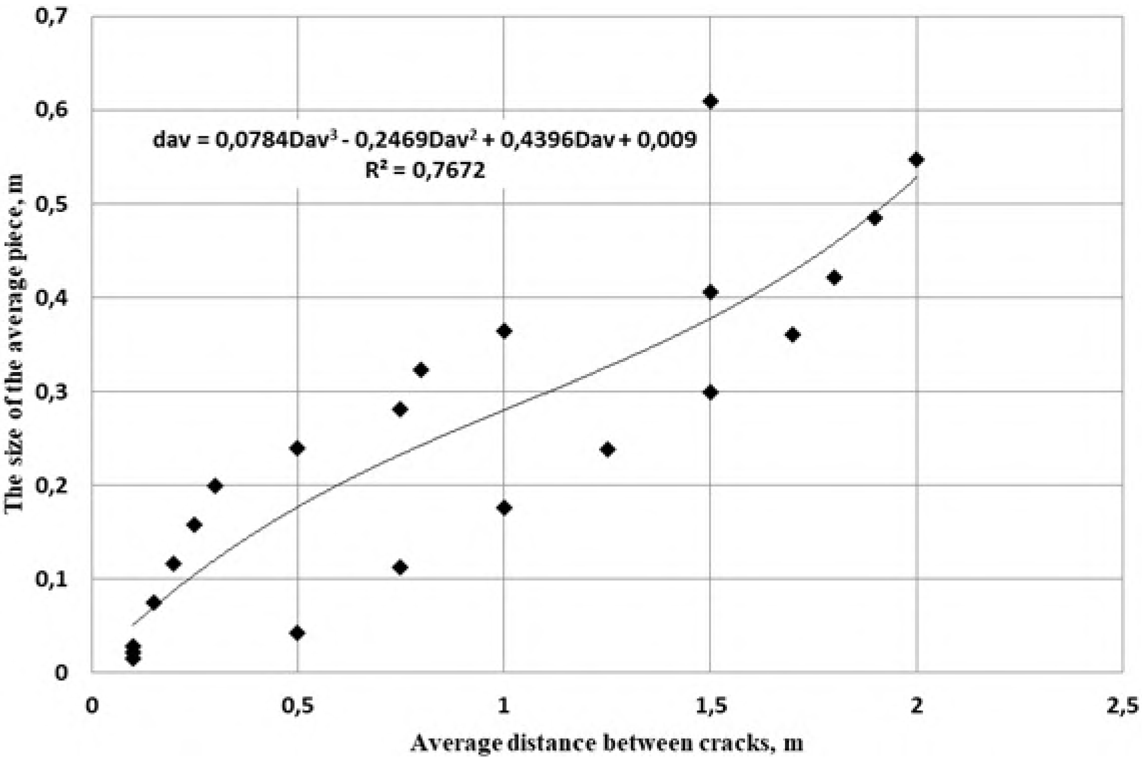

Figure 2. Graph of the dependence of the size of the average piece on the average distance between cracks in the massif of rocks.

will use the classification data and form a data array (table 5) and visualize it in figure 2.

With the help of regression-correlation analysis, the dependence with the largest correlation ratio was obtained, which is described by a polynomial of the third degree.

4. Conclusions

A general formula was obtained for calculating the average size of a piece of blasted rocks depending on the properties of the rocks, their blockiness, the used explosives and its specific consumption. The specified formula can be used to calculate the average size of a piece of rock with any physical properties and various blasting conditions. Also, with the help of regression-correlation analysis, the dependence of the expected size of the average piece of crushed blasted rocks on the blockiness of the rocks was established.

The results of scientific research can be used for large-scale forecasting of the cost of extracting a mineral. Also, the application of the proposed approach will help to assess the investment attractiveness of deposit development at the pre-project stage.

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Tool for management and planning of the fuel and energy complex taking into account the production potential of coal-mining enterprises

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Tool for management and planning of the fuel and energy complex taking into account the production potential of coal-mining enterprises

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Abstract. The article presents a toolkit of manage balanced functioning of the fuel and energy complex with the aim of improving the system of state support for coal mines and harmonizing the interests of the enterprise, national interests, and interests of product consumers. To solve the problem, a comprehensive approach was used, which includes the assessment of the investment attractiveness of the enterprise, the determination of the production potential, and the determination of the possibility of transition to the break-even mode. The process of planning ways of saving the industrial potential of coal-producing regions can be considered as a reflection of a multidimensional space (initial and design values) into a one-dimensional (the amount of investment funds). The reduced task to the selection of the smallest number of factors that would most adequately reflect the internal potential of mine in terms of economic added value – as a result of the interaction factors of economic activity of coal mine. The scientific novelty lies in the fact that the formed matrix model of the commercial coal products balance is aimed at avoiding an imbalance in the sectoral coal market and significantly reducing unjustified costs both on the part of the state and on the part of mining enterprises due to the optimization of planned and forecast indicators. The practical significance lies in conducting an actual assessment of coal enterprises state of Ukraine and determining break-even limits, which made it possible to formulate recommendations for attracting volumes of financial resources.

1. Introduction

The energy industry of Ukraine directly depends on the coal industry, as basis of the country's industrial development [1, 2]. It is based on the principles of energy saving and effective use of all available energy resources [3]. Despite the recent world trends of decarbonization [4–7], the coal industry in Ukraine is the main, core, city-forming one and, despite the decline in prestige, remains one of the main industrial branch.

One of the main directions of the task implementation of improving the reliable operation of coal mines is not only improvement of coal mining technology [8] and develop workings, but also the development of a tool for managing and planning the production potential of coal mining enterprises.

Amosha, Shemiakina and Ponomarenko [9], Cherevatskiy and Volchin [10] developed practical recommendations to substantiate the rational level of production for unprofitable mines of the Central District of Donbas, and the degree of intensity of use of fixed capacities was also determined. In addition, these approaches allow not only to develop recommendations, but also to make long-term forecasts. Therefore, in order to stabilize the state of the industry, it is necessary to conduct an analysis of the balance between labor resources, involved capital and the final level of production – the application of existing criteria generally accepted in the world economy allows solving the problems of effective development of mineral deposits. The logic of these assumptions is explained by the presence of rational design area [9], that is, regardless of the mining and geological conditions of the deposit and the existing technical and economic indicators, there is always a set of parameters that allow to reach the break-even level, that is, to choose a rational format of life activity [11].

Nieć [12] states that in order to increase production efficiency, it is necessary to balance the flows of input and output resources depending on the production scenario. On the basis of a retrospective analysis of the state of the industry, Li et al. [13] made an assumption that currently the industry cannot be brought out of a crisis state without attracting investment. At the same time, further delay will lead to stagnation, the transition from "stable decline" to the uncontrolled curtailment of production capacities, so it is necessary to develop mechanisms for assessing the expediency of supporting coal mines [14].

Numerous scientific studies are devoted to the problems of the functioning of the coal industry in the conditions of the formation of a market economy. In particular, ways of increasing the efficiency of the industry management system [15], innovative and investment mechanisms [16], means of reducing the unprofitability of state mines [17], etc. were considered. On the basis of the research results, it is possible to form a general scheme of the economic mechanism for supporting the capacity of coal industry enterprises, one of the components of which is the budget subsidy subsystem. In the studies of Ukraine economists, a mechanism was developed for quantitative assessment of the condition of each mine from the point of view of investment attractiveness. The impracticality of mass closure of mines without appropriate social means has also been proven.

However, in modern conditions, along with the study of certain aspects of coal mining, the study of the mechanism of revitalization of the potential of the industry, disrupted by the instability in the eastern regions of Donbas, is of particular relevance. One of the priority measures today is the normalization of the price policy in relation to competition with natural gas, the identification of objects of investment, in order to ensure the expanded reproduction of the potential of the coal industry. Some aspects of this problem are outlined in this paper.

Based on the above, the purpose of this work is to develop a tool for management and planning of the fuel and energy complex, taking into account the production potential of coal mining enterprises of Ukraine.

2. Results and discussion

To solve the problem, a complex approach is applied, which is based on the implementation of the neoclassical production function in the form of the Solow model for the analysis of the state in the coal mining industry, as well as the assessment of the economic reliability coefficient for the development of a tool for the management and planning of the energy complex, taking into account the production potential of coal mining enterprises of Ukraine.

The efficiency of the operation of the enterprise can be estimated by the ratio of incoming flows (capital) and outgoing (level of production) resources, while the innovative component plays a significant role. Analysis of the relationships between resource flows allows choosing optimal scenarios.

The relationship between the balance models of all levels of management is especially important, regardless of the "planned" or "market" orientation of coal mining enterprises.

The formed matrix model of commercial coal products balance is aimed at avoiding an imbalance in the sectoral coal market and significantly reducing unjustified costs both on the part of the state and on the part of mining enterprises due to the optimization of planned and forecast indicators.

It has been proven [18] that coal remains virtually the only available and relatively reliable energy source in Ukraine. In particular, in the Energy Strategy of Ukraine for the period until 2030, the country's coal industry, despite the difficult geological conditions, outdated material and technical base and growing unprofitability, is recognized as the foundation of the domestic energy industry. But the presence of 5-7 billion tons of economic reserves, which lie in extremely difficult conditions, is not yet a reason for optimism. In Europe, mines with layers occurrence and production conditions approaching Ukrainian ones have long been closed. That is why it is necessary to improve the budget policy management system to reduce the level of unprofitability of state mines, methods of targeted investment to support the capacity of enterprises depending on their rating, the state of mining industry, the quality and volume of remaining reserves.

Without the liberalization of the coal market, it is quite difficult to establish a system of supporting the capacity of the mining fund, since the cost of production is significantly higher than the market price. An exception can be only vertically integrated companies that receive the main profit not from mined coal, but from the result of its use – electricity or metal [19]. As you know, the main problem of improving the structure of the mine fund of the industry has not been solved due to untimely and insufficient financing of support for each ton of the installed mine capacity. In addition, until now, a clear concept of regulating the productive flows of coal mines in terms of the sale of finished coal products has not been created. In the new conditions of the formation of the economy of Ukraine through integration into the world community, the level of unprofitability of coal enterprises due to price management, the excess of the cost price over the price and the amount of subsidies should correspond to the following expression [20,21]:

$$\mathbf{F} = P + S + G \to \min \tag{1}$$

where: P – sale price of mined coal; S – the need to subsidize 1 ton; G – subsidy opportunities of the mine owner.

Since all terms in expression (1) are positive, minimizing the sum means minimizing each term. The minimization of the first term P is equivalent to the reduction of prices to the minimum permissible value. The minimization of the second term S means the maximum satisfaction of subsidy applications associated with the excess of cost over price. In particular, if all subsidy applications are fulfilled, then the term S acquires its minimum value equal to zero. The minimization of the third term G leads to a decrease in the amount of subsidies. At the same time, all components in expression (1) are independent and their minimization realizes opposite tendencies. Indeed, the decrease of the first term P, i.e. the price of products, is accompanied by an increase in the amount of subsidies and the underfulfillment of subsidy applications, therefore, an increase in the terms S and G. A decrease in the second term S means the maximum fulfillment of subsidy applications, which leads to an increase in the amount of subsidies to the price, i.e. an increase in the terms P and G. A decrease in the third term G – the amount of subsidies – is accompanied by a worse satisfaction of subsidy applications, which causes an increase in the price. The comparative value of the coefficients of the objective function should reflect the balance of the influence of these opposing tendencies.

Such a mechanism is designed to prevent the spread of a vicious system – the greater the losses of the mine, the more subsidies from the state. In other words, it allows to determine the mine's potential of production. At the same time, in the management system of the mine's potential, the interests of the enterprise, national interests, and the interests of product consumers are coordinated. When modeling such a system, the interest of the enterprise is expressed in the target function, and the national interest is expressed in the system of restrictions on the production and sale of certain grades of coal.

Unfortunately, the old economic system of attracting and distributing additional resources from above depending on the change in the level of planned indicators has been preserved in the coal industry. Such a balance model, by itself, is inert to prices. At any price (planned, calculated, optimal, market), its calculation parameters do not change. This made it possible to use estimated prices (including planned ones), so inter-industry proportions were not supported by prices, but artificially, for example, by the planned distribution system. For such a system, prices always remain an external element. At the level of local production systems, the imbalance of different types of prices (figure 1), the presence of the division of the industry into "conditional-planned" and market, leads to the existence of a certain number of producers of commodity products, whose local optima (interests) come into conflict with the global optimum (nationwide interest)

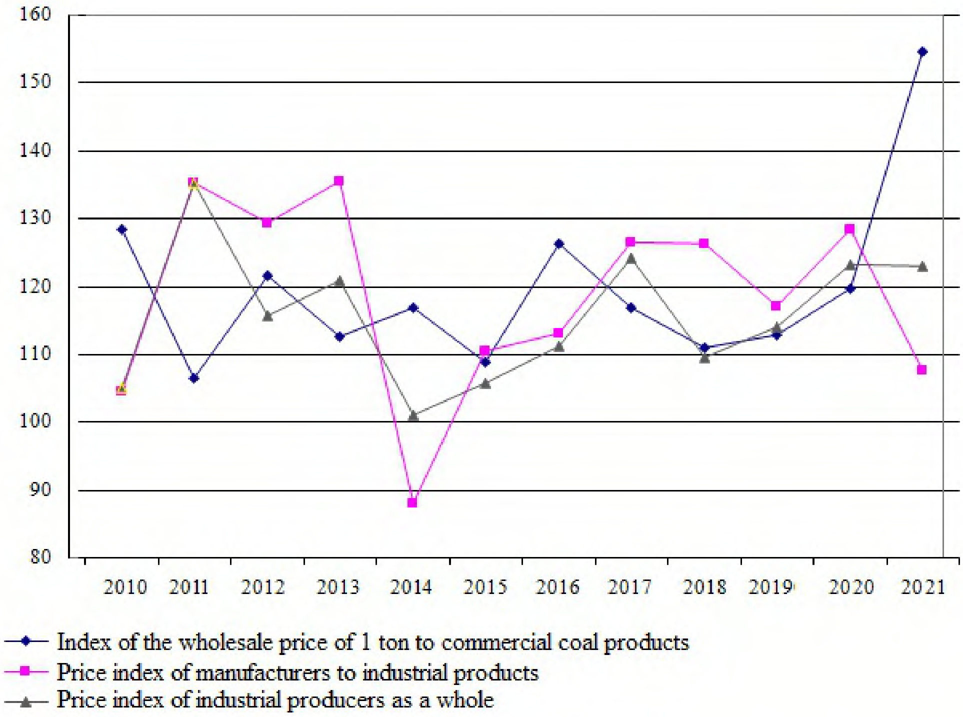

Figure 1. Imbalance of price indicators of producers of commercial coal product.

Thus, ratio (1) is economically interpreted as follows: the optimal volume of production at an individual enterprise based on its orientation to market prices is achieved when marginal variable costs are equal to market prices. If prices do not change, these production volumes provide the maximum profit for the enterprise. That is, it is once again confirmed that it is the market prices that are the regulator of the balanced development of the coal enterprise. The matrix models of the balance of commercial coal products formed on the basis of this are aimed at avoiding imbalances in the sectoral coal market and significantly reducing unjustified costs both on the part of the state and on the part of unprofitable coal mines due to the optimization of planned and forecast indicators. Therefore, when drawing up a carbon balance, the existence of such phenomena should be taken into account. Of course, it is necessary to fight them at the legislative level, but, as practice shows, on currently this struggle is not effective. Therefore, the first necessary step for the formation of an optimal balance model is the determination of all participants in the coal market, the actual volumes of coal production, as well as the schemes according to which it is distributed for consumption [22, 23].

The basis for determining the quantitative indicators of production and consumption of commodity products of enterprises of a separate industry is the forecast balance (matrix) model (figure 2), which includes the final output of all production units of the industry (II quadrant), costs of its production (I quadrant) and total income (III quadrant), which includes the sum of wages and net income of all enterprises in the industry. Quadrant IV of the balance is located at the intersection of the final output columns and the income rows, and it reflects the final distribution and use of the total income of the industry. At the same time, the term "final" refers to products that enter the sphere of production into the sphere of final use – for consumption, accumulation, and export.

Manufacturers	Consumers				Final production	Gross production
	1	2	…	In total		
1.	x_{11}	x_{12}	…	x_{1n}	Y_1	X_1
2.	x_{21}		$\boxed{\mathrm{I}}$		$\boxed{\mathrm{II}}$	X_2
…	x_{n1}	x_{n1}	…	x_{nm}		X_3
In total	$\Sigma\ \ \Sigma x_{ij}$					
Import					Y_n	… X_n
Pay	V_1	V_2	…	V_n	V_k	
Net profit			$\boxed{\mathrm{III}}$		$\boxed{\mathrm{VI}}$	
	m_1	m_2	…	m_n	m_k	
Gross production	X_1	X_2	…	X_n		X

Figure 2. Typical balanced (matrix) model.

Such a model was named the main task of production planning and allows the process of optimization calculations and analysis of optimal solutions to be divided into three stages:

(i) finding the best production methods and minimum labor costs for a given vector of final products based on the model;
(ii) determination of the volume and structure of the variable part of the final product (it is possible to use different criteria and maximization conditions);
(iii) calculation of a balanced production plan that ensures the production of all final products with limited resources.

Under these conditions, it is reasonable to use the upper and lower limits of the mine capacity and variable consumer demand. The essence of the approach is as follows. The specified values D_i^{min} and D_i^{max}, which correspond to the lower and upper limits of the production capacity of the mines. Values $b_j (j = 1, 2, \ldots, n)$ determine the probable volumes of consumption of finished coal products in the j–th points, C_{ij} – revenue from the sale of 1 ton of products, taking into account fluctuations in the level of prices, demand and the amount of budget subsidies; X_{ij} – number of units of products delivered from the mine (factory) from point i to point j. It is necessary to find a nomenclature of placement of production capacities in a specific coal mining region so that the economic potential of the mines does not decrease.

Mathematical formulation of the problem. Find the set Xij to maximize the functional F

$$\mathbf{D}_i^{min} \leq D_i^{max} (i = 1, 2, ...m) \tag{2}$$

$$\sum_{i=1}^{m} X_{ij} \neq b_j (j = 1, 2, ...m) \tag{3}$$

$$\sum_{i=1}^{m} D_i^{min} = \sum_{j=1}^{n} b_j \geq D_i^{max} \tag{4}$$

$$\mathbf{F} = \sum_{i=1}^{m} \sum_{j=1}^{n} CijXij \to \max \tag{5}$$

We consider it expedient to solve this expression as an open optimization model with limited bandwidths of suppliers (mines) and stochastic values of the parameter C_{ij}. Moreover, determining the optimal values of the sought production volumes X_j is not the main task. More important are the answers to the questions about the impact on the efficiency of the mine of each of the resources used, as well as the technical and economic parameters that form the potential of the enterprise in terms of prices and reducing the degree of unprofitability. It should be emphasized once again that the degree of utilization of production resources of mines is so inefficient that the shadow price of these resources cannot in any way correspond to their real value, as laid down in the duality limit theorems [24].

If we assume that the coefficients in the expression for the objective function are random values, then the values of all controlled variables X_j are determined in the absence of information about what values the parameters of the functional C_j will actually take. Such a situation in real conditions occurs when solving the task of planning the operation of mines, when future sales prices, which depend on poorly predictable changes in demand and the future cost of materials and energy at the time of developing the plan, are strictly unknown.

The obtained results do not contradict numerous studies in this field. Therefore, the developed tool for management and planning of the fuel and energy complex, taking into account the production potential of coal mining enterprises of Ukraine, is appropriate.

3. Conclusions

Until now, the approach to the quantitative description and consideration of socio-political factors, strategy and tactics of economic activity in the coal industry is implemented within the traditional scheme of inter-industry balance. In particular, in macroeconomic models, the variables characterizing the economic activity of the state are usually classified as exogenous, and the scenario blocks that form a set of exogenous variables are postulated or justified by political hypotheses.

The degree of unprofitability and the level of unprofitable state subsidization mines should be determined in such a way that the minimization of the price of coal products is built in parallel with the maximum satisfaction of subsidy applications for the tariff agreement and the excess of the cost price over the price. This achieves an appropriate balance of prices depending on the priority of mines in terms of coal quality and the level of economic reliability of the enterprise.

The relationship between the balance models of all levels of management is especially important, regardless of the “planned” or “market” orientation of coal mining enterprises. The formed matrix model of the balance of commercial coal products is aimed at avoiding an imbalance in the sectoral coal market and significantly reducing unjustified costs both on the part of the state and on the part of mining enterprises due to the optimization of planned and forecast indicators.

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Researching the optimal combination of UAV equipment for performing surveying measurements and software for processing the results

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Researching the optimal combination of UAV equipment for performing surveying measurements and software for processing the results

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Abstract. In recent years, there has been a development and popularization of conducting mine surveys through remote methods. This is a result of the continuous development of the mining industry, where projects are becoming increasingly complex. Therefore, the application of remote surveying is expected to grow rapidly in the coming years. In the future, UAV (Unmanned Aerial Vehicle) technology, satellite imagery, and LiDAR surveying can completely transform the measurement life cycle in mining enterprises. The conducted research helped justify the best instruments for mine surveying and the software for processing field results, which were used in practical experiments. Measurements of mining volumes were carried out using the selected instruments and software, and the results obtained were compared with the reference values. The conducted work allowed for the evaluation of the possibility of using UAVs for mine surveying and determining the optimal choice of instruments and software for conducting such activities.

1. Introduction

Currently, aerial surveying is the most cost-effective and relevant method for geodetic monitoring of large territories. Unmanned technologies have firmly established themselves as tools for engineering tasks in the field of geodesy. The evolution of constructive innovations, reduction in size and form changes, and varying equipment configurations have led to the classification of Unmanned Aerial Vehicles (UAVs) [1]. Diverse measurement methods have emerged depending on the type of task execution. The evolution of UAV usage has touched nearly all areas of engineering, from measuring linear objects to dendrological studies of forest masses. Consequently, the widespread adoption of unmanned technology, particularly in geodesy, could not bypass mine surveying.

Mine surveying equipment for mining operations is a labour-intensive process requiring highly qualified personnel, expensive equipment, and specialized software. During open-pit mining, various mine surveying tasks need to be addressed, including monitoring work progress and mapping assessments of mining volumes and dumps. Unmanned technologies are indispensable for capturing various types of mining activities. They allow mine surveying tasks to be performed with minimal fieldwork costs, although specific skills and knowledge are required for the post-processing of acquired data.

In the future, UAV, satellite, and LiDAR surveying technologies will be capable of completely transforming the measurement life cycle in mining enterprises. Photo and video materials, along with 3D models created based on them, enable the determination of production scale, tracking and conducting measurement work, monitoring the progress of work, and updating information in real time.

Utilizing unmanned aerial vehicles to address geodetic tasks will allow for a broader range of tasks to be completed in shorter periods with less risk for the operators. Many urgent geodetic tasks exist today, but they often require excessive time. This can be associated with the volume of work or the inaccessibility of the object. Using UAVs during field topographic-geodetic research significantly reduces the time and cost of such work.

One of the main drawbacks of remote sensing is the influence of weather conditions and the presence of restrictive objects near the shooting area. However, these issues can be mitigated. For example, shooting can be conducted during weather conditions that minimally affect the process, and limits for shooting can be established for each device. Based on the above, it can be concluded that by considering all factors affecting the shooting process, optimal conditions for conducting the surveys can be selected.

Considering the above, the application of UAVs will increase the efficiency of mine surveying. Therefore, our research focuses on determining the feasibility of using UAVs for mine surveying and selecting optimal equipment and software for these tasks.

The research holds significant value in modernising the process of conducting mine surveying through open methods. Just a few years ago, the most effective way to obtain contours and terrain data was through the use of digital photogrammetric stations (DPS). These systems automated the processes of internal and external image orientation and the creation of digital terrain models.

Today, software solutions such as Pix4D, Reality Capture, Photoscan, and others are designed to generate three-dimensional models using photogrammetric methods efficiently. These programs have become particularly popular with the advent of accessible UAVs, allowing for rapid and effective aerial surveying.

Implementing this innovation significantly accelerates and enhances the safety of the mine surveying process. To achieve the best results, selecting suitable instruments for surveying and software for processing is essential, ensuring the highest accuracy in the results. Considering those as mentioned earlier, it was decided to conduct this research.

The research aims to study the feasibility of using UAVs for mine surveying and determine the instrumentation and software for fieldwork processing that can provide more accurate results.

2. Theoretical background

In recent years, the need for terrain information in many industries has no longer been satisfied solely by the use of topographic maps in analogue and digital formats. Detailed information about objects' spatial position and heights is required to address various engineering tasks.

Cartographic materials, aerial and satellite images, and field survey data serve as sources for modelling digital terrain models [2]. Andreev and Zhilin stated that UAV aerial surveying offers numerous advantages compared to obtaining data through satellite imagery and piloted atmospheric aircraft. The key prerequisites for these advantages include the operational acquisition of aerial images, the ability to capture images from low altitudes, and the capability to operate in emergency zones without risking the lives and health of pilots [3].

Using UAVs in mining has two main advantages. Firstly, it is the time it takes to perform fieldwork and the ability to conduct remote operations. Secondly, UAVs equipped with various types of sensors can quickly survey an area, both in emergency situations and when detecting potential hazards [4].

Li and Choi classified the applications of drones in the mining industry, including open-pit mining and underground and abandoned mines, as shown in table 1 [5]. One method of surveying using UAVs involves the use of additional equipment such as Light Detection and Ranging (LiDAR). The technology of conducting surveys with this device is described in the work of Staroverov and Gaykin. The operation principle of the LiDAR system is similar to radar. LiDAR emits laser beams that reflect off the ground objects. The instrument measures the time intervals between the emission and return of the signal, determining the length of the path travelled by the beams [6].

Table 1. Applications of UAVs in mining [5].

Open-pit mining	Underground mine	Abandoned mines
• Mine surveying • 3D mapping • Slope stability • Construction monitoring • Asset management	• Geotechnical characterization • Rock size distribution • Gas detection • Mine rescue	• Settlement monitoring • Reclamation • Landscape mapping • Gas storage detection • Acid drainage monitoring

Jarahizade and Salehi conducted a comparison of software for processing UAV data. Specifically, they evaluated the use of Agisoft Metashape, Pix4d, and DJI Terra for processing drone-based forest mapping. According to their research, specific software is recommended for achieving certain results [7].

Niederhaeuser et al. conducted a study comparing five sensors and four different software packages for modelling vegetation cover. Their findings revealed that Agisoft and MicMac were the most suitable for their tasks [8].

Berber, Munjy, and Lopez noted that the most popular programs for image processing are Agisoft Metashape and Pix4d [9].

3. Methods

The main research methods include literature analysis, factor analysis, analysis of instruments for performing surveying using UAVs, and analysis of software used in processing field materials. The theoretical part of the work involves studying works related to UAV-based surveying and processing of results in open-pit mining.

To assess the readiness level of surveying services and determine the economic feasibility of using remote surveying equipment, a comparative analysis method was used.

The study employed a systems analysis to evaluate the technical component in the field of surveying and explore ways to improve surveying using UAVs.

The research focuses on the method of economic and practical analysis, modern UAVs for surveying, and software for processing materials obtained after the survey. The factor and situational analysis methods were also used to address potential issues and factors influencing the development of the study.

As of today, obtaining data on the performance of surveying software related to UAV-based surveying is impossible because it requires detailed testing and evaluation. Therefore, the main methods for researching software include analyzing works related to surveying and comparing their functionality. For investigating software, the analysis method was used to explore options for survey processing, the possibility of an automated processing system, and the ability to create a 3D model.

These methods served as the basis for selecting, researching, and comparing instruments for remote surveying and software for processing field results.

Using digital and mathematical modeling methods, the obtained results were processed, allowing for the assessment of the qualitative characteristics of conducting surveying. The data obtained demonstrate the feasibility of introducing innovations into the surveying system, enhancing the productivity and safety of the conducted work. The analytical research in this work shows that the proposed surveying methods contribute to the effective execution of surveying.

Utilizing the mentioned methods, a survey of the mined area of the enterprise was conducted using UAVs. The survey results were processed, and the volumes of the work areas were calculated. A comparison of results obtained using different instruments and software was performed. Based on this comparison, the feasibility of using UAVs for surveying was determined, and the optimal choice of instruments and software for conducting surveying was justified.

4. Results

Modern remote measurement methods allow for obtaining high-quality and objective information about objects and processes on Earth's surface. They are widely applied in various fields, including the oil and gas industry.

Geometrization of deposits is the process of creating digital models of deposit objects used for planning and conducting geological exploration works and deposit development. The use of modern remote measurement methods for the geometrization of deposits allows for:

- Reducing costs for geological exploration.
- Increasing the accuracy and reliability of geological models.
- Expanding the possibilities of geological exploration works.

One of the keys to successful measurements at a mining enterprise is a well-chosen method of measurement execution. Analyzing the purpose and goal of the measurements, determining the final vision of the results, and considering the locality, dimensions, deposit conditions, peculiarities, and financial expenses, it is essential to choose the method of measurement execution.

Today, there are many means of remote measurements. In this work, the main remote methods suitable for the geometrization of deposits were considered, such as:

- Aerial photography.
- 3D scanning (LiDAR).
- Electromagnetic survey.

Each of the methods for conducting remote measurements has functional differences from one another. Therefore, when choosing a specific method for surveying, it is necessary to compare the data of different methods. Several popular methods for remote surface surveying were considered for research, and their advantages and disadvantages were investigated. The list of main advantages and disadvantages is provided in table 2.

According to the data in table 2, it is evident that each method has its own advantages and disadvantages. By comparing the surveying methods, we can conclude that the most significant drawback among the mentioned ones is the limited spatial resolution, which affects the final model and the accuracy of the measurements conducted. This limitation is associated with the Electro Reconnaissance method. Since precision is of great importance in cadastral surveys, the choice for further practical research in this work was Aero-photography and 3D scanning (LIDAR).

Table 2. Comparison of remote measurement methods.

Technology	Aerial photography	3D scanning (LIDAR)	Electrical reconnaissance
Advantages	• Speed; • Clarity of shooting; • Safety of filming	• High accuracy and resolution; • Wide range of measurements; • Ability to collect data; in real-time; • Ability to collect data over long distances.	• Speed; • Availability; • Ability to collect various data
Disadvantages	• Dependence on weather conditions	• Limitation of weather; conditions; • A device for transportation during shooting	• Dependence on weather conditions; • High costs • Limited resolution

With the growing interest in aerial photography using UAVs, the number of announcements from modern digital photogrammetric systems developers about introducing special algorithms and sets of functions for working with geodata in their software products is increasing.

Among the well-known photogrammetric systems, some of the most prominent software products include:

- AgiSoft Metashape;
- Drone Mapper;
- Pix4D.

Each of the presented products for UAV data processing has certain differences, making it challenging to choose specific software. The most popular software for surface survey processing was investigated during the research, and their main advantages and disadvantages were identified. The key pros and cons of each of the mentioned software products are presented in table 3.

Comparing the software based on table 3, it can be concluded that, in general, all products are similar in their characteristics. The comparison revealed a significant drawback in the Drone Mapper software, namely, a limited number of images for processing. The advantages of AgiSoft Metashape and Pix4D include a simple and convenient survey processing interface. Thus, for the research on cadastral survey processing, AgiSoft Metashape and Pix4D are chosen.

In modern conditions, where speed and accuracy in obtaining information are crucial, manual volume calculation methods do not meet the requirements of modern companies. Therefore, modern methods, such as Agisoft Metashape software, are applied. After constructing a digital terrain model with the necessary quality and accuracy, volume calculations can be initiated.

One advantage of Agisoft Metashape software is that volume calculation can be performed directly in the program without using third-party applications. This saves time since there is no need to export the model. The volume calculation principle is similar in both programs and is carried out automatically. To determine the volume, it is necessary to outline the contour of the required figure.

To assess the effectiveness of using UAVs for cadastral surveying, the volume of worked-out rock mass at the Leznikivskyi granite deposit was calculated. The measured contour is shown in figure 1.

Table 3. Comparison of software for processing survey results using UAVs (unmanned aerial vehicles).

Software	AgiSoft Metashape	Drone Mapper	Pix4D
Advantages	• Simple interface; • Automatic recognition of landmarks function; • Survey lity to adjust processing factors of the survey; • Export capability to various file formats;	• Two tabs during operation: "Results" and "Tasks and Processes"; • Informative interface; • Optimized software operation	• Convenient interface; • Automated survey processing; • Support for personal cloud service
Disadvantages	• Lack of prior automatic configuration	• Processing of surveys without coordinate reference is not possible; • Maximum scale 1:2000; • There are limitations on the number of images	• Limited user impact on processing; • Imperfect manual editing; • Georeferencing to landmarks with low accuracy

Figure 1. Contours of the research areas.

During the research, surveying of the worked-out rock mass of the enterprise was performed using each of the proposed devices (Aero-photography and 3D scanning (LIDAR)). After

Table 4. Comparison of obtained volume calculation results for the worked-out rock mass.

Plot No.	Volume, m^3 Pix4Dmapper (UAV)	Volume, m^3 Agisoft Metashape (UAV)	Volume, m^3 Pix4Dmapper (LIDAR)	Volume, m^3 Agisoft Metashape (LIDAR)	Volume, m^3 Civil3D (Theodolite Survey)
1	1066	1058	1061	1050	1040
2	452	445	448	439	443
3	350	342	350	341	338

Table 5. Error from various calculation methods.

Plot No.	Error (%) Pix4Dmapper (UAV)	Error (%) Agisoft Metashape (UAV)	Error (%) Pix4Dmapper (LIDAR)	Error (%) Agisoft Metashape (LIDAR)
1	2.4	1.7	2.0	1.0
2	2.0	1.0	1.1	0.9
3	3.4	1.2	3.4	0.9

fieldwork, data processing was carried out using the selected software (AgiSoft Metashape and Pix4D), meaning each survey was processed in both programs.

To assess the accuracy of volume calculations obtained from processing data of aerial photography with UAV and LIDAR, it is necessary to compare the results with the reference values indicated in the table (table 4). The reference value chosen is the volume of the worked-out rock mass obtained based on the execution of the theodolite survey.

According to the data in table 4, we can conclude that the obtained values are quite close. Based on the results in table 4, the error (in %) from the reference value was calculated and is presented in table 5.

Based on table 5, we can conclude that all four variants of cadastral surveying can be recommended. Since the maximum error is 3.4 percent, which is an acceptable value, and

Table 6. Average error values for different calculation methods.

Pix4Dmapper (UAV)	Agisoft Metashape (UAV)	Pix4Dmapper (LIDAR)	EAgisoft Metashape (LIDAR)
2.6	1.3	2.2	0.9

Table 7. Range of error deviations for different calculation methods.

Pix4Dmapper (UAV)	Agisoft Metashape (UAV)	Pix4Dmapper (LIDAR)	EAgisoft Metashape (LIDAR)
1.4	0.8	2.4	2.5

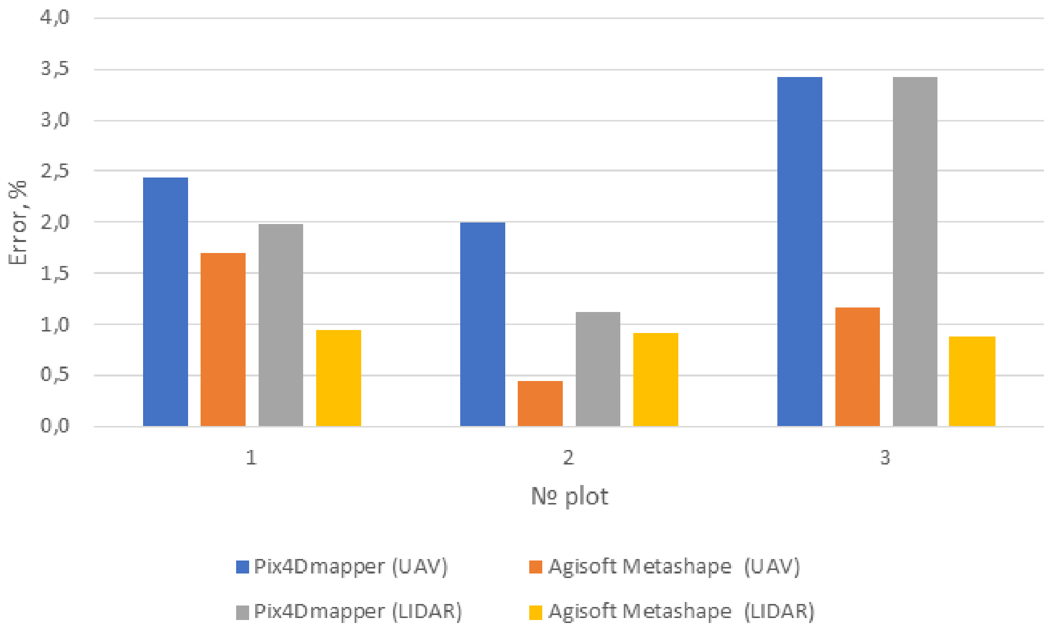

Figure 2. Comparison of errors.

the maximum error does not exceed 15 percent [10].

The table data is used to compare errors by plots and calculation methods, as depicted in figure 2.

Based on figure 2, we can conclude that the smallest error occurs when surveying with LIDAR and processing the data with Agisoft Metashape. Considering this, we recommend conducting cadastral surveying with this combination of equipment and software.

Using the results from table 5, the calculation of average values for each variant and the range of deviations for each variant were performed, as presented in table 6 and table 7, respectively.

Due to the data in table 6 and table 7, graphs were constructed, which are depicted in figure 3 and figure 4, respectively.

By analysing the graphs, it can be concluded that the smallest average error and the smallest range of deviations occur when using LIDAR for cadastral surveying, and the data processing is done with Agisoft Metashape. Next, in terms of accuracy, is the option of using UAV for cadastral surveying and data processing with Agisoft Metashape.

The discrepancies in volume measurements obtained using different surveying instruments are much smaller than when using different software. Considering the above, it can be concluded that the choice of the surveying instrument has a lesser impact on accuracy than the choice of software. Considering this, we recommend conducting cadastral surveying using the specified combination of equipment and software.

5. Conclusion

The research compared various surveying instruments for remote sensing and software for processing field data. As a result, the optimal combination of using LIDAR for cadastral surveying and processing data with Agisoft Metashape was selected.

A comparison of the volumes of mined material using four proposed surveying and field data processing schemes to the reference value obtained through theodolite surveying and processing in Civil 3D was conducted. The results of this comparison show that all proposed variants are acceptable, as the maximum deviation from the reference value is 3.4 %, within the acceptable

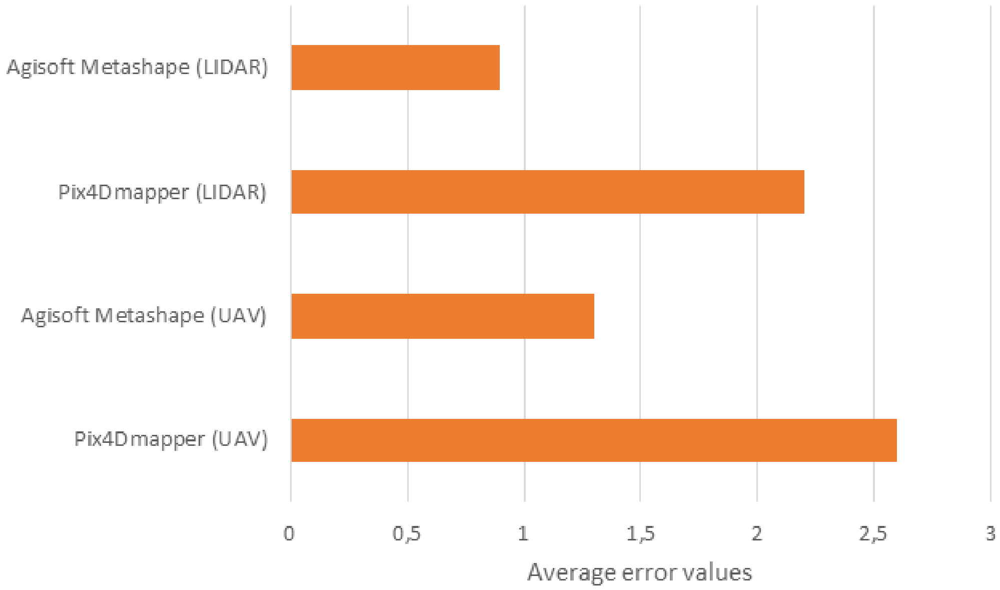

Figure 3. Average error values for different calculation methods.

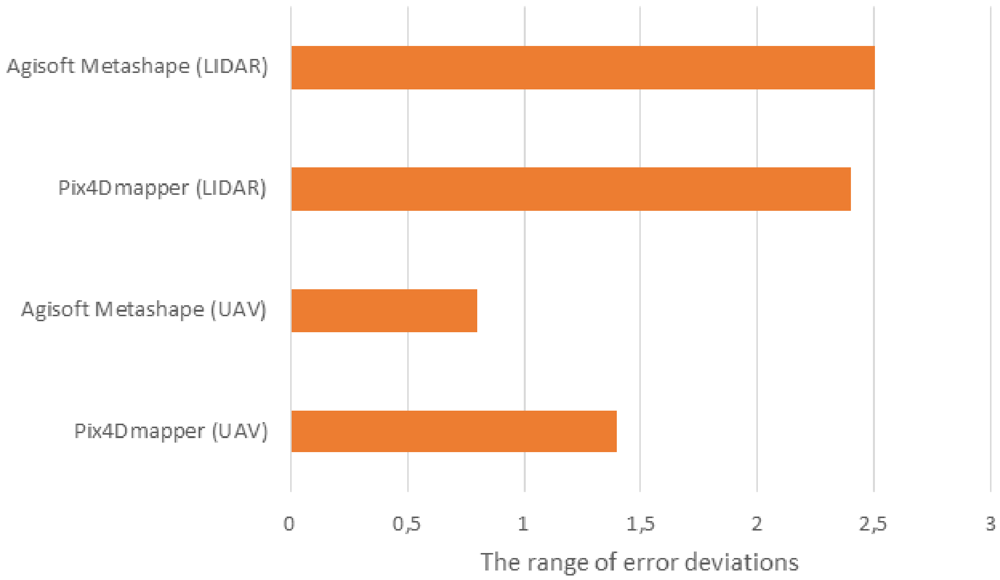

Figure 4. Range of error deviations for different calculation methods.

error limit of 15 % for volumes up to 20,000 m^3 [10]. Since the smallest measurement error occurs when surveying with LIDAR and processing the data with Agisoft Metashape, this surveying method is the most accurate.

To enhance the efficiency of cadastral surveying, it is recommended to conduct the survey using UAV, utilising LIDAR for surveying and Agisoft Metashape for data processing. Implementing this surveying approach will provide the necessary accuracy, efficiency, and safety in conducting the work.

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Analysis of quantitative and qualitative parameters of gas mixture in thermal processes of mine medium

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Abstract. The article examines the problem of the occurrence and spread of fires in mines caused by the increased emission of methane and coal dust. The method of mining space isolation with the help of fire-prevention stopping, reducing the oxygen concentration and creating an inert medium, was studied. It has been experimentally established that thermal action on coal without air access causes the formation of combustible gases such as methane, carbon monoxide, hydrogen and unsaturated hydrocarbons. The peculiarities of the formation of a multicomponent gas mixture in the temperature range from 400 to 900^{0}C were determined. High temperature causes a gas phase yield rise, which leads to an increase in its heat of combustion according to a quadratic dependence. It was found that the methane yield increases up to 600^{0}C , and then its decrease in the gas mixture is observed due to decomposition into hydrogen and atomic carbon at temperatures above 700^{0}C . High values of combustion heat of gases are determined by methane at temperatures up to 800^{0}C , after which the influence of hydrogen rises with high temperatures. The obtained data of the gas mixtures combustion heat make it possible to establish the qualitative and quantitative parameters of the thermal process occurring in the isolated mining space. This can be used to calculate the heat balance of the mining medium and to simulate the thermodynamic processes occurring during mining fires.

1. Introduction

The coal industry of Ukraine plays an important role in providing the country with energy resources and raw materials for industry, especially during a wartime. Currently, there is a very urgent need for coal as the main source of energy in war conditions due to the versatility of coal combustion technologies at thermal power plants. Here are the main advantages:

- flexibility in responding to consumer needs (the operation of coal thermal power plants allows for prompt response to changes in electricity production needs, which during military actions can be critical for ensuring the energy supply of whole country);
- independence from external factors (coals make it possible to reduce dependence on foreign suppliers of nuclear fuel or raw materials for renewable energy sources);
- simpleness of operation and availability (coal thermal power plants are relatively easy to operate and require less time to restore a fast power supply, and the modularity of such stations will allow them to be deployed at the local level and provide power supply even due to obstacles in the transportation of energy carriers, caused by military actions).

Despite the problems caused by the war, the stable operation of coal mines continues. By 2014, there were 145 mines in Donetsk coal basin. Due to the hybrid aggression of the Russian Federation and the occupation of a part of Donetsk region, 96 mines remained in the non-government controlled area, and 49 in the government-controlled area [1]. Currently, 21 mines operate in the Donetsk region, including 15 state-owned ones [2, 3].

In 2022, state-owned coal mining enterprises mined 173 thousand tons of coal, and this figure decreased over a prolonged period. However, in January 2024, the production amounted to 178 thousand tons, in February – 197 thousand tons, and by the end of March, the production reached 221 thousand tons, which is 24 % more than in January [4].

These statistical data indicate the relevance and importance of coal mining and processing in Ukraine for the stable generation of electricity in thermal power plants. However, these processes are associated with numerous risks to the lives and health of miners, because in coal mines the working conditions are characterized by a significant number of hazardous factors. These include methane emissions, the stressed state of the coal-rock mass, presence of closed space, limited access of air, water and the presence of electrical equipment. [5]. Under certain circumstances, all of this can lead to explosions and fires. In addition to all this, coal mining at great depths is complicated by difficult mining geological and technical conditions, which include gas content, the degree of self-ignition of coal, the explosiveness of coal dust and the ability of coal to form dust. Because of this, the danger of emergency situations with serious consequences in the technological process of mining of mineral deposits in underground conditions increases, which poses a threat to the life and health of miners [6].

Every year, numerous accidents occur at coal enterprises, which can be caused by rock collapses, sudden coal and gas outbursts, explosions of coal dust-air mixtures and underground fires. In the period from 2016 to 2018, an increasing number of accidents and emergency situations were observed in Ukrainian mines, which emphasizes the threat to the safety of miners and the stability of coal production. The main conclusions from the analysis are given below [7]:

- the total number of accidents and emergency situations almost doubled, from 18 cases in 2016 to 37 in 2018; this indicates the difficult state of coal mining conditions;
- the total number of accidents and emergency situations almost doubled, from 18 cases in 2016 to 37 in 2018; this indicates the difficult state of coal mining conditions;
- despite the stable number of general accidents, there is an increase in the number of underground fires and exogenous accidents, which indicates the problems of fire control and it prevention;
- the number of evacuated persons increased from 1,918 persons in 2016 to 3,244 persons in 2018, which indicates the seriousness of accidents and the need to improve rescue operations;
- the duration of accidents liquidation and emergency situations increased significantly from 1094 hours in 2016 to 3748.7 hours in 2018, which indicates the complexity and duration of liquidation works;
- enterprises suffered losses that increased from UAH 61,280,000 in 2016 to UAH 77,693,000 in 2018, this can have a serious impact on the financial condition of mining companies.

2. Problem statement

In general, the occurrence of fires of both endogenous (caused by self-ignition of coal) and exogenous (caused by external heat impulses) nature in worked-out area has become more frequent. Huge difficulties arise with the elimination of the fire consequences in mines, where coal mining is carried out at the same time. In such conditions, it is not always possible to extinguish an endogenous fire by direct attack. The elimination of such fires can take tens of years and complicate mining processes [8].

In terms of caused damage, fires with methane and coal dust ignition are mostly catastrophic. They are the most destructive, complicated and long-lasting in terms of their elimination. They are also accompanied by significant human victims, lead to large material losses and damage underground communications and equipment. In recent 10 years, there have been 13 such accidents in which 5 or more people were injured, 9 of them were directly related to the explosion of methane and coal dust. This indicates about violation of safety regulations, insufficient financing of coal mines, and a low level of implementation of new, modern, safe coal mining technologies

Any underground fire, regardless of the cause of its occurrence and the type of combustible material, is accompanied by complex physical and chemical processes that lead to a change in the composition of the mine atmosphere in general, as well as in the area of flame flashing. In coal mines, the composition of the mine atmosphere is constantly monitored. Any deviations in its composition from permissible values can characterize various processes occurring in mining tunnels. Therefore, a violation of the gas regime in such tunnels can lead to the formation of dangerous explosive mixtures, when there is an intensive yield of methane from natural and man-made cracks.

The application of existing solutions for the prevention and spread of fires in underground tunnels is complicated by the problem of the air-tightness of the isolated space and the management of the parameters of the mine atmosphere in it. To accelerate the extinguishing of underground fires, the method of mine space isolation is used by constructing of fire-prevention stopping, which contributes to the further reduction of oxygen concentration and the formation of an inert medium around the ignition point. It can happen in different ways: by thermochemical processes with oxygen absorption, injecting of inert gases into the mine tunnel, filling of the mine space with recirculating combustion products.

All of this can be further complicated by the shutdown of the main ventilation fan due to rocket and artillery shelling and the lack of electricity. For example, as a result of a projectile hitting, a coal mine lost power, and ventilation of the mine tunnels was maintained through natural draft. Meanwhile, initial signs of a fire were detected in the extraction area, leading to the decision to isolate part of the mine. Due to the complex mining-geological and security conditions in the conflict-affected region, standard methods for determining the development of fires are not feasible. Therefore, there is a need to determine the quantitative and qualitative indicators of fire gases based on their volume and combustion heat in conditions of limited mine space and oxygen-free medium to prevent the development of endogenous fires.

3. Related work

It is well known that in the conditions of a limited space of a coal mine and an oxygen-free medium, the determination of quantity and quality indicators of fire gases is a key aspect for preventing the development of endogenous fires. Significant results were obtained when studying the composition of combustion products in isolated mine spaces, which were reflected in [9–14]. The search for the causes of explosions in coal industry and the development of ways to prevent endogenous fires in deep mines were carried out by Bulat, Minieiev and Smolanov [15], Pashkovskyi [16], Gluzberg [17]. In these works, the basic physical conditions of coal oxidation were formulated and a theoretical interpretation of this mechanism was presented.

The analysis of existing works has shown that thermal impact on mine medium can take place both in an oxygen-free environment and with the use of oxidizers. These processes primarily involve the decomposition of the organic matter, the recombination of the splitting products and the formation of thermodynamically stable final substances: the solid residue, the liquid products and the gas phase. The physical essence of the thermal process of coal is as follows. According to the Fuks-Krevelen pyrolysis theory [18] the process can be accurately described as a sequence of chemical reactions, involving the decomposition of organic matter occurred in the adjacent layer and in the outer surface of the particles.

Physical-chemical transformations begin to appear at temperatures of about 500^0C. However, at 350^0C constitution moisture and adsorbed carbon gases, such us carbon dioxide, methane, air component were released. Consequently, organic matter decomposition does not occur, but likely, certain changes in its internal structure transpire. At temperatures greater than 450^0C a certain quantity of water vapor and carbon dioxide are evolved, that is a result of complicated chemical reactions, involving, in general, in the external polar groups. In the temperature range of 500-600^0C processes of coal structure decomposition are increased. The intensive emission of water vapor, carbon dioxide, some amounts of hydrogen sulfide and organic compounds of sulfur are occurred. At this stage, the oxygen content in the coal-contained material is markedly reduced. However, in this temperature range weak chemical bonds are splitting. Profound changes in the internal structure of the organic matter have not been observed yet. At temperatures above 600^0C the organic matter are intensively decomposed with the formation of free and unstable substance groups. Occurred recombination processes were developed in two directions: formation of condensed products characterized by a high content of carbon and low content of hydrogen; formation of liquid and gaseous products enriched with hydrogen. Deep decomposition of organic matter and emission of liquid products are completed generally at a temperature of about 800^0C. These processes are accompanied by releasing of hydrogen, methane, carbon monoxide and nitrogen. During further temperature heating the yield of methane, nitrogen, oxygen, carbon dioxide were not observed, however, the hydrogen and carbon monoxide were formed in significant quantities. In conclusion, it is necessary to identify the following options of thermal process of coal decomposition:

- low-temperature thermal process (600-800^0C), at which the maximum yield of the liquid phase and the solid residue, as well as the minimum yield of the gas phase with high calorific value;
- medium-temperature thermal process (800-1000^0C), in which there is an increase in the yield of the gas phase with a decrease in its heat of combustion and a decrease in the yield of liquid products and solid residue.

However, the insufficient amount of experimental research did not allow to investigate the processes in isolated space during thermochemical reactions of oxidation due to the difficulty of sampling fire gases in mining and geological conditions [19].

So, the goal of the study is to produce further information regarding the following question: what kind of gas should be produced during coal combustion in isolated space to identify signs of underground fire development.

4. Methods

Therefore, in order to solve this problem, there were carried out an investigation, which made it possible to establish experimentally a quantitative and qualitative parameters of coal combustion products [20]. As a matter of fact, carbon, oxygen and hydrogen, which are part of the molecular composition of coal, turned into methane, carbon monoxide and water vapor. The degree of such transformations was determined by the rate of chemical reactions according to the Arrhenius law [21].

Low grade sapropel coal, which is mined in the Lviv-Volyn coal basin, was chosen as the material for the study of the influence of the combustion process on the quantitative and qualitative indicators of fire gases. The results of technical and elemental analysis data of coal samples are listed in table 1.

The table 1 shows data on the content of carbon C, hydrogen H, nitrogen N, oxygen O, the total amount of sulfur S_{total}, moisture W, ash content per dry mass $A_d$and the yield of

Table 1. Results of elemental and technical analysis of coal and rock samples.

Material	Structural composition, %							
	C	H	N	O	S_{total}	W	A_d	V_{daf}
Sapropel coal sample 1	34.8	2.5	0.7	3.2	0.3	1.8	56.7	52.2
Sapropel coal sample 2	36.8	2.8	0.9	3.4	0.8	1.2	54.1	59.9

volatile substances per dry ash-free mass V_{daf} in the organic matter of the above mentioned coal material.

The essence of the experimental method was to heat a certain mass of coal to a temperature from 400 to 900°C without access of air with obtaining a solid residue and collecting gaseous and vaporous products formed in the thermal process.

The scheme of the laboratory installation is shown in figure 1.

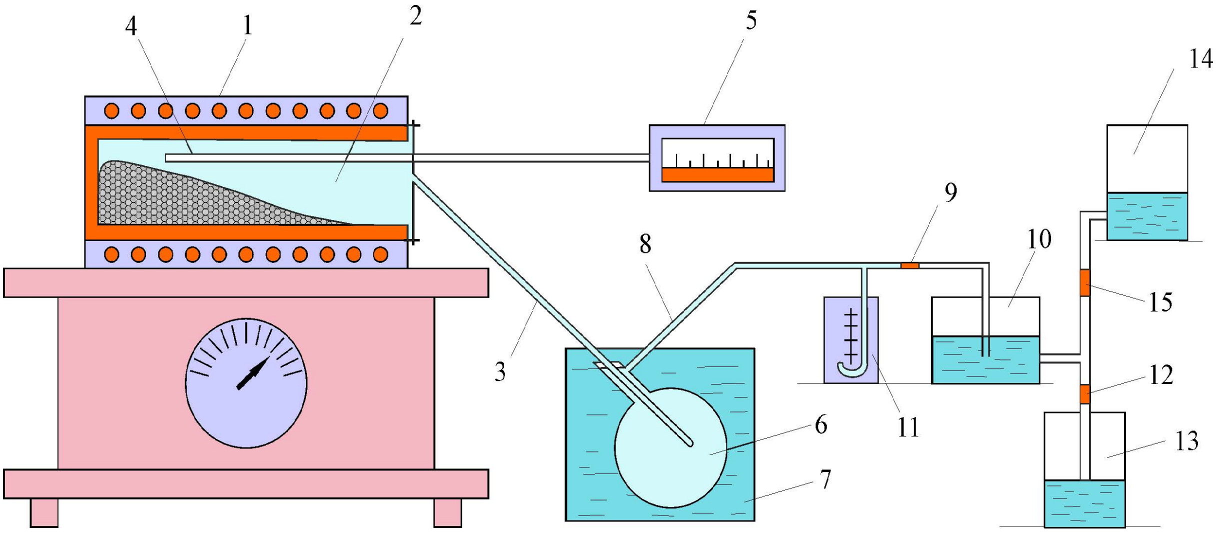

Figure 1. The scheme of the laboratory installation for the study of coal combustion processes: 1 – electric furnace, 2 – retort, 3 – volatile outlet tube, 4 – thermocouple, 5 – galvanometer, 6 – receiving flask, 7 – vessel with a cooling liquid, 8 – gas outlet tube, 9 – valve, 10 – gasometer, 11 – U-shaped manometer, 12 – valve, 13 – water measuring cylinder; 14 – leveling vessel; 15 – valve.

At furnace 1, a retort 2 is installed, where some amount of coal material was placed. The retort was a thick-walled cylindrical container made of heat-resistant steel, which consists of a removable cover and a special volatile outlet tube 3 with a thermocouple 4. The temperature in the furnace was recorded using a thermocouple and a galvanometer 5. A receiving flask 6, placed in a vessel 7 with a cooling liquid, is connected to the gas outlet tube 8. The pressure, at which the thermal process took place, was measured by a water U-shaped manometer 11, and was maintained by pouring water in a metered manner into the water measuring cylinder 13. The measuring system is regulated with the help of leveling vessel 14 and valves 9, 12 and 15.

The yield of reaction products was determined as follows. A sample of the carbon-contained material was poured into the retort 2, closed with a lid, which was tightened with bolts for sealing, and heated, observing a certain regime of temperature rise. Liquid products, released by heating of the sample, were condensed in the receiving flask 6, and the gases, passing through the outlet tube of the flask 8, entered the gasometer 10 for further analysis. The amount of gas phase was determined indirectly by subtracting the weight of liquid products and solid residue from the weight of the initial sample.

The non-condensed part of the volatile substances was directed through the gas outlet tube 8 to determine their chemical composition. For this purpose, a special apparatus was used, in which there were seven identical absorption vessels filled with a bundle of glass tubes to increase the contact surface of the analyzed gas with the following reagents:

- solution of caustic potash for absorption carbon dioxide CO_2 and hydrogen sulfide H_2S;
- solution of potassium bromide, saturated with liquid bromine, for absorption of unsaturated hydrocarbons C_nH_m;
- alkaline solution of pyrogallol to absorb oxygen O_2;
- ammonia solution of copper semichloride for absorption carbon monoxide CO;
- solution of sulfuric acid for absorption from the analyzed gas of ammonia vapors formed in the gas after passing through an ammonia solution of copper semichloride;
- table salt solution, which serves as a receiver for gas when burning hydrogen H_2;
- solution of caustic potash, which serves as a receiver for gas and absorption of carbon dioxide CO_2 during the combustion of methane CH_4.

Nitrogen N_2 was measured in a pre-cooled installation after burning methane CH_4 and hydrogen H_2.

So, according to the provided information, the laboratory installation could carry out an analysis and determine the quantitative content of the following components of the gas phase: carbon dioxide CO_2 and hydrogen sulfide H_2S (simultaneously), unsaturated hydrocarbons C_nH_m, oxygen O_2, carbon monoxide CO, hydrogen H_2, methane CH_4 and nitrogen N_2.

5. Results and discussion

It should be mentioned, that at this stage of complex investigations about the influence of quantitative and qualitative indicators on the fire gases combustion, only experimental data for one average statistical sample were given. Four temperature intervals for four gases were used to construct the graphs, which contributed to better visualization and mathematical processing of the obtained data.

The gas mixture included hydrogen H_2, carbon monoxide CO, methane CH_4 and unsaturated hydrocarbons C_nH_m. The results of the experimental researches are presented in figure 2.

The researches have established the following important parameters of gas mixtures during coal combustion in oxygen-free medium:

- at a temperature of 400^0C, CO was released the most
- at a temperature of 600^0C, H_2 was released the most;
- at a temperature of 800^0C, H_2 was released the most;
- at a temperature of 900^0C, H_2 was released the most.

Calculating the heat of combustion, the following assumptions were made. Firstly, due to the small content of carbon disulfide, this gas was not taken into account. Secondly, the combustion of the gas mixture took place under normal conditions (the amount of oxygen in the air is 21.8%).

The calculating results of the heat of gas mixture's components combustion and their percentage in relation to the amount of methane depending on the temperature are presented in figure 3 and figure 4.

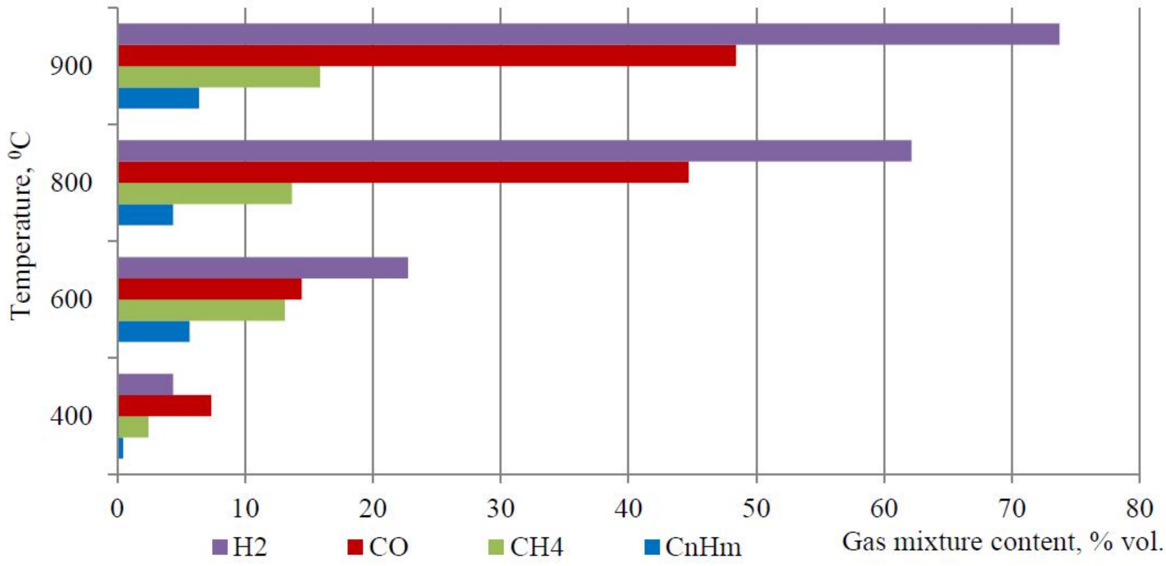

Figure 2. Yield of combustible gases depending on process temperature.

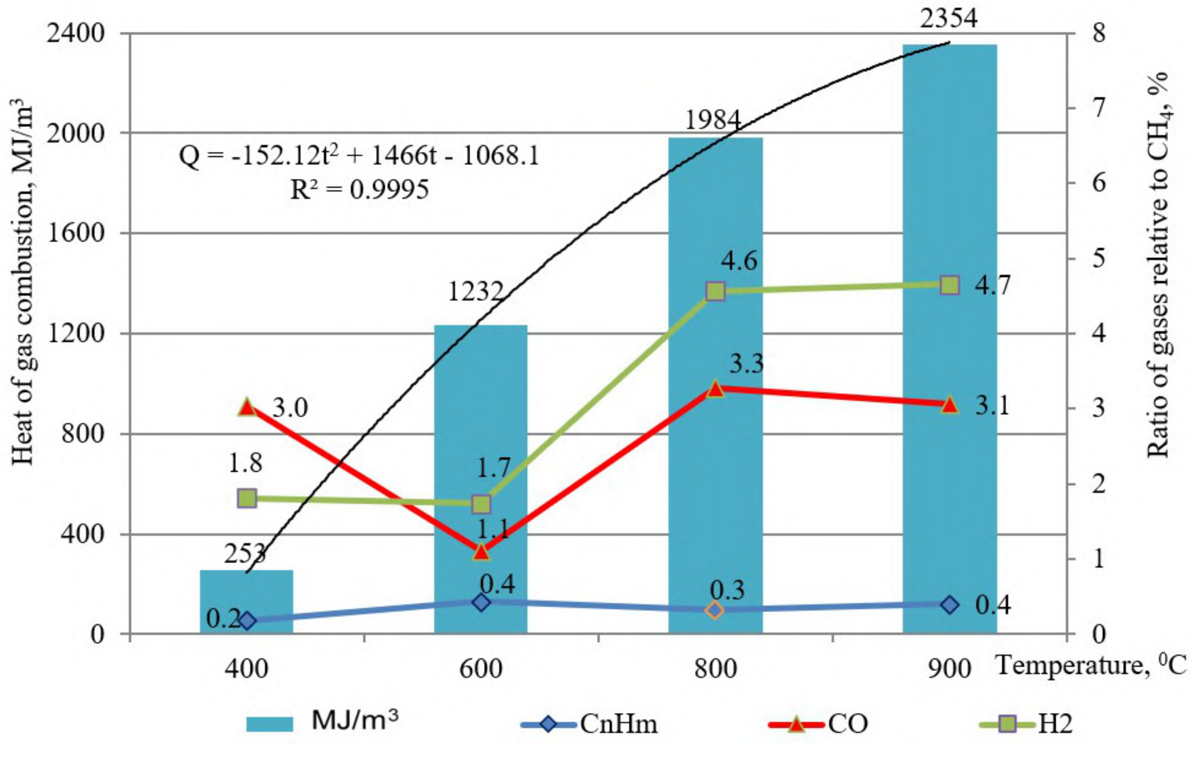

Figure 3. The ratio of combustible components and heat of gas mixture combustion in relation to the amount of methane depending on the process temperature.

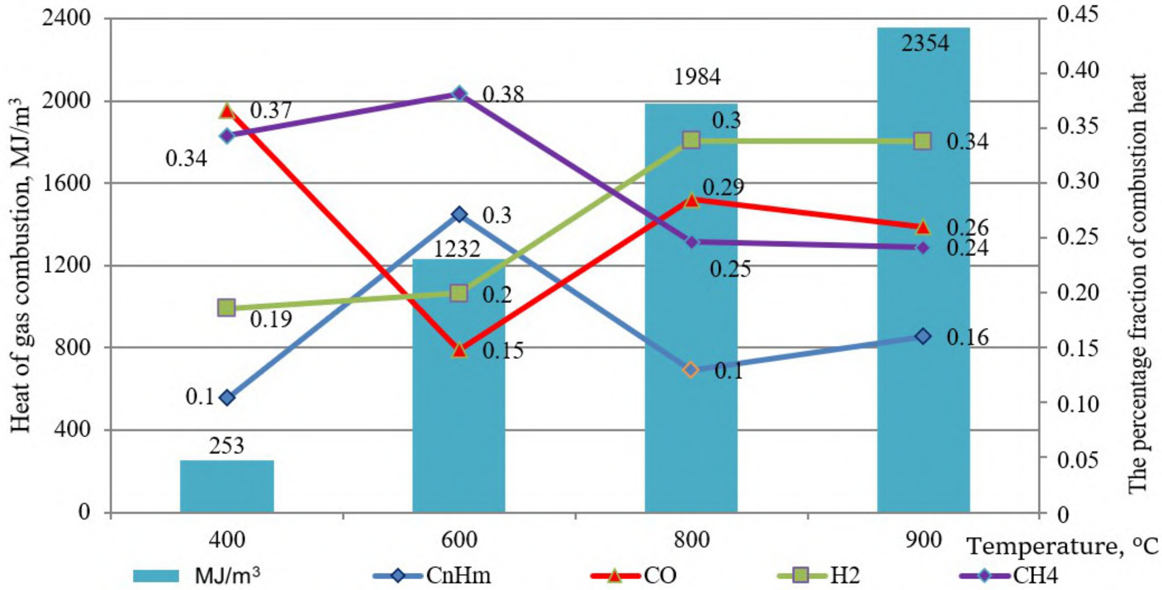

Figure 4. Dependence of the calculated combustion heat of the percentage fraction of each gas on the process temperature.

According to figure 3, the following conclusions can be given. In the temperature range from 400 to 900^{0}C with the increasing of temperature increases the gas mixture yield, and, as a result, the heat of its combustion according to the quadratic dependence

$$Q = -152.12 \cdot t^2 + 1466 \cdot t - 1068.1$$

with the coefficient of determination $R^2 = 0.9995$.

At a temperature of 400^{0}C, three times the release of carbon monoxide and twice the release of hydrogen compared to methane were observed. At a temperature of 600^{0}C, two times more hydrogen was released compared to methane, and the amount of carbon monoxide was formed as much as methane, and the heat of combustion of this mixture increased 6 times due to the large amount of methane. At a temperature of 800^{0}C, five times the release of hydrogen and three times the release of carbon monoxide compared to methane were observed, and the heat of combustion of this mixture increased by 1.6 times due to the large amount of hydrogen and carbon monoxide. At a temperature of 900^{0}C, five times the release of hydrogen and three times the release of carbon monoxide compared to methane were observed, and the heat of combustion of this mixture increased by 1.2 times due to the large amount of hydrogen and carbon monoxide.

According to the conducted researches (figure 4), at a temperature of 400^{0}C, methane (34%) and carbon monoxide (37 %) contribute the biggest fraction the heat of gas mixture combustion, at a temperature of 600^{0}C – methane (38 %) and unsaturated hydrocarbons (30%), at a temperature of 800^{0}C – hydrogen (30 %), carbon monoxide (29 %), methane (25 %), at a temperature of 900^{0}C – hydrogen (34 %), carbon monoxide (26 %), methane (24 %). In figure 4, let's consider the main heat-generating gases. At temperatures of 400^{0}C, as well as 800^{0}C and 900^{0}C, the percentage ratio of methane and carbon monoxide is practically the same. At a temperature of 600^{0}C, the percentage ratio of methane and carbon monoxide is 2 to 1.

6. Conclusions

So, the obtained statistical data indicate the relevance and importance of coal mining and processing in Ukraine for the stable generation of electricity in thermal power plants. However, these processes are associated with numerous risks to the lives and health of miners, because in coal mines the working conditions are characterized by a significant number of hazardous factors. These include methane emissions, the stressed state of the coal-rock mass, presence of closed space, limited access of air, water and the presence of electrical equipment.

In general, the occurrence of fires of both endogenous (caused by self-ignition of coal) and exogenous (caused by external heat impulses) nature in worked-out area has become more frequent. Huge difficulties arise with the elimination of the fire consequences in mines, where coal mining is carried out at the same time. In such conditions, it is not always possible to extinguish an endogenous fire by direct attack. The elimination of such fires can take tens of years and complicate mining processes.

The analysis of existing works has shown that thermal impact on mine medium can take place both in an oxygen-free environment and with the use of oxidizers. These processes primarily involve the decomposition of the organic matter, the recombination of the splitting products and the formation of thermodynamically stable final substances: the solid residue, the liquid products and the gas phase. As a matter of fact, carbon, oxygen and hydrogen, which are part of the molecular composition of coal, turned into methane, carbon monoxide and water vapor. The degree of such transformations was determined by the rate of chemical reactions according to the Arrhenius law.

The following combustible gases are formed during thermal action on coal in air-free medium: methane, carbon monoxide, hydrogen and unsaturated hydrocarbons.

It was found that in the temperature range from 400 to 900^0C with the increasing of temperature increases the gas mixture yield, and, as a result, the heat of its combustion according to the quadratic dependence $Q = -152.12 \cdot t^2 + 1466 \cdot t - 1068.1$ with the coefficient of determination $R^2 = 0.9995$.

Methane yield increases up to a temperature of 600^0C, then its content in the gas mixture decreases. This can be explained by the decomposition of methane into hydrogen and carbon at temperatures above 700^0C. This process helps to raise the amount of hydrogen in this temperature range.

High values of combustion heat of the gas mixture in the temperature range from 400 to 600^0C are achieved due to methane. When the temperature increases, the heat of combustion due to hydrogen and carbon monoxide raises.

Obtained values of combustion heat of gas mixtures made it possible to establish qualitative and quantitative parameters of the thermal process. These data will be used in the future for the calculation of the thermal balance of the mine medium and modeling of thermodynamic processes arising as a result of mine fires in the isolated space.

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Improvement technique surveying observations of the displacement

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Improvement technique surveying observations of the displacement

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Abstract. The purpose of the research is to increase the efficiency of work on monitoring deformation processes and shear in the areas of influence of mining activity. The research methodology is based on the analysis of instrumental observations of the objects negatively affected by mining activities. As a result of the research, special attention was focused on the use of innovative instruments for instrumental measurements and software processing the data. The scientific novelty of the obtained results consists in using a comprehensive modern digital and satellite methods for performing instrumental observations on profile line reps, which makes it possible to obtain a more complete feature of the deformation process and information about the current state of the ground surface and other objects located in the research area, which makes it possible to increase the accuracy of the prediction for a certain period of time and quickly verify the dimensions of the displacement zone and its spreading limits. The practical significance of the research is that its results will contribute to ensuring the safe operation of the deposit and the development of more effective measures to protect the environment and mitigate the negative impact of mining activities on the area and buildings located in the zone of their influence. The studies have shown that the automated method of comparing point clouds to sinkhole areas obtained from two digital models can produce significant errors. These errors, when determining the spatial position of points, can reach 10-15 meters. In the case of a "manual" set of picket points, the errors do not exceed 0.1-0.2 m, but the time of data processing increases significantly, i.e., increasing the accuracy of determining the desired values requires a decrease in the efficiency of this process.

1. Introduction

The objects of mining enterprises in Kryvyi Rih are characterized by difficult mining conditions. There may be several mining sites in one area, and a deposit is developed by several mining companies simultaneously. Because of this, the harmful influence on a particular structure can be determined only by the displacement vector. One of the important tasks of the surveying team of a mining enterprise is to ensure the protection of buildings and structures from the negative impact of mining activities [1]. The use of only classical or modern methods of performing surveying monitoring of the displacement process doesn't always allow obtaining complete information about the process and solving this scientific and practical task at the appropriate level [2–5]. Only the complex use of these methods gives the best effect.

At the Kolachevsky mine, when studying the process of surface displacement in the area affected by underground mining activities, to ensure the safe operation of buildings and structures, a comprehensive method is used, which includes: the method of profile lines

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with linear-angle measurements; satellite method with the determination of the coordinates of points using GNSS equipment; ground photogrammetric survey; RTK survey of new cracks and terraces; aerial survey for a comprehensive survey of the displacement zone and adjacent territories [6–8]. Based on practical experience, it can be argued that only such a comprehensive approach can ensure informed decision-making on the protection of structures and the environment [9–14].

2. Choosing a methodology for performing deformation studies

Additional profile lines were laid in the sinkhole area by specialists from the Department of Surveying at Kryvyi Rih National University in 2010. Systematic aerial surveys of the sinkhole and adjacent territories for their comprehensive survey have been implemented since 2019 [6–8], and systematic ground stereotopographic surveys since 2018.

Satellite methods have been implemented at mining enterprises in Kryvyi Rih since 2007, but were of limited use until 2017. Since 2017, monitoring of landslide and deformation processes using new technologies has been carried out on an ongoing basis. A comprehensive monitoring method was introduced with the intensification of landslide processes in 2017-2021, which resulted in: an increase in the landslide area and the process beyond the design limit; an increase in the actual size of the hazardous landslide zone on the hanging side.

Before the 2010 collapse, the observation station at the top of the mine consisted of 32 ground benchmark, which are metal pins 1500-1800 mm long and 25-30 mm in diameter. In addition, the observation station included 20 wall benchmark, which were installed in the middle XX century. After the collapse in 2010, the Kryvbasproject State Enterprise developed a project for additional profile lines, taking into account the current situation.

When developing a deposit of ore or non-metallic mineral resources, for which the displacement processes have not yet been fully defined or sectoral regulations have not yet been developed, measures to protect structures and the environment should be carried out on the basis of recommendations of a specialized research organization, such as, for example, Research and Development Mining Institute of Kru=yvyi Rih National University (KNU). Therefore, the recommendations of Research and Development Mining Institute KNU additionally includes the location of profile lines in the area of the kindergarten, boiler room, and other buildings and structures, with a frequency of observations of 4 times a year.

Recommendations for the safe exploitation of structures and improvement of surveying monitoring in 2023 at the Kolachevsky mine were provided by the Department of Surveying and Geodesy of the State Enterprise "Ukrrudprom". According to the recommendations and requirements of the instruction, the intervals between the benchmark are approximately 20 meters, but sometimes, due to the presence of underground utilities and the impossibility of laying benchmark in the private sector, etc.

It is known that the leveling benchmark profile lines is carried out according to the class III leveling method, in one direction by closed ranges or closed passages or hanging passages in the forward and reverse directions [15]. The leveling is performed with a high-precision level (Zeiss Ni2 level is used for leveling on the mine territory). At the same time, the permissible misalignment in closed and double drifts did not exceed 10 mm $\sqrt{L}$, where L is the length of the drift in km (figure 1).

The lengths of the intervals between benchmark were measured using a Sokkia SET630R electronic total station with a standard deviation of 2 mm in the forward and reverse directions. The centering of the reflector is performed using a bipod. This measurement technique allows obtaining the length of the intervals between the benchmark with a relative accuracy of no more than 1:10 000.

Earlier, when studying the landslide process using observation stations, linear measurements and geometric leveling were used, but later it turned out that this wasn't always enough to

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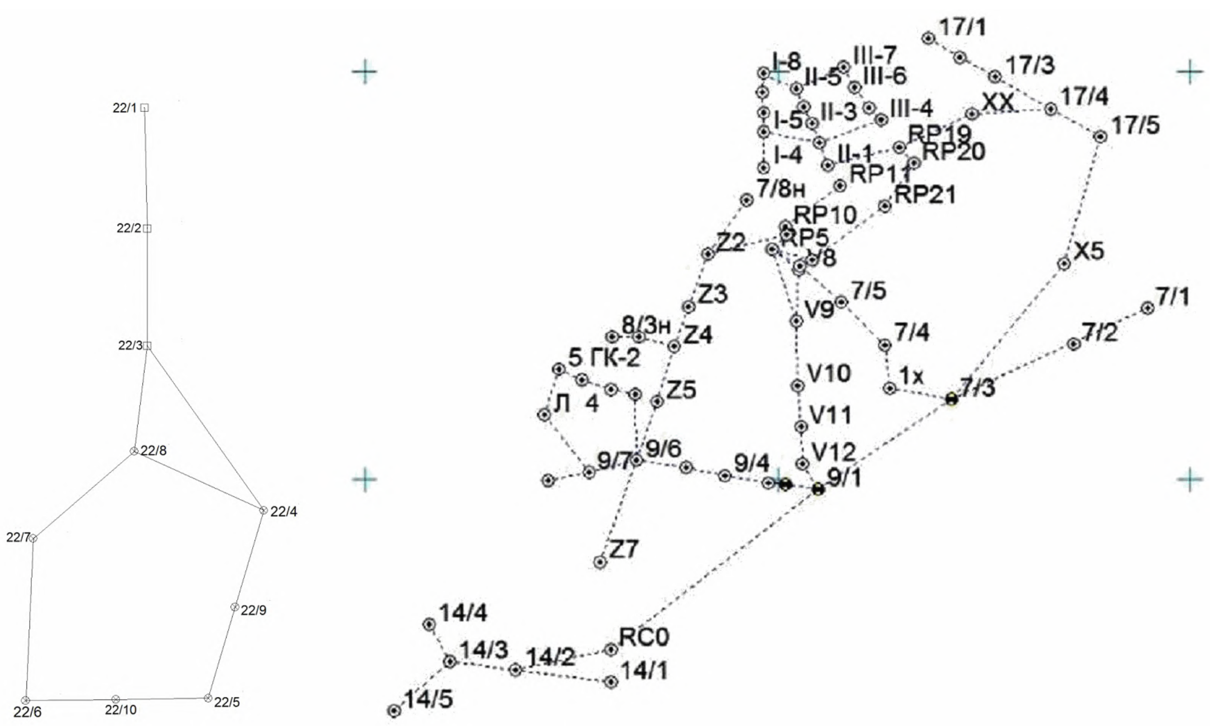

Figure 1. Schemes of leveling moves kindergarten area and industrial area.

obtain a complete characterization of the displacement process. Therefore, in order to obtain more complete information, the coordination of profile line benchmark using GPS observations was introduced.

To link the initial references, three class 1 triangulation points were used (Dubova Balka, Brato-Semenivka, Tovsta), which are located at distances of 7 to 10 kilometers from the Kolachevsky Mine. At these points, work was done to study their condition and determine their coordinates. These points are important for the enterprise, as they were taken as the starting points when creating the mine's coordinate system. Their coordinates were determined using GPS, with the duration of observations at the station being two hours. As a result of this work, their coordinates were determined with an accuracy of 3 mm and 6 mm in plan and height, respectively. Thanks to these measurements, the coordinates of the original benchmarks and changes in their position over a period of more than 60 years have been updated. To perform these works, 4 Top-con Hiper+ receivers and one Topcon HiperPro were used. In terms of accuracy class, they correspond to high-precision devices with an accuracy deterioration of 0.5 mm per kilometer in the planned and elevation positions. Figure 2 illustrates the scheme of binding to triangulation points.

High-precision satellite monitoring are used to monitor the position of 19 benchmarks, 5 of which are located mine's territory (figure 3). When performing measurements on the benchmarks, the static mode is used with a measurement recording interval of 5 seconds. At the same time, the time of standing on the benchmark is from 30 to 60 minutes, and the cutoff angle is 13 degrees. A prerequisite for high-precision measurements using GPS is to ensure minimal influence of error sources or, if possible, their exclusion. It is known that the accuracy of measurements is affected by the characteristics of spacecraft, such as the geometry of satellites, etc. Reducing the recording interval to 1 second of measurement doesn't affect the accuracy of coordinate determination, but it does increase the file size by 3-5.

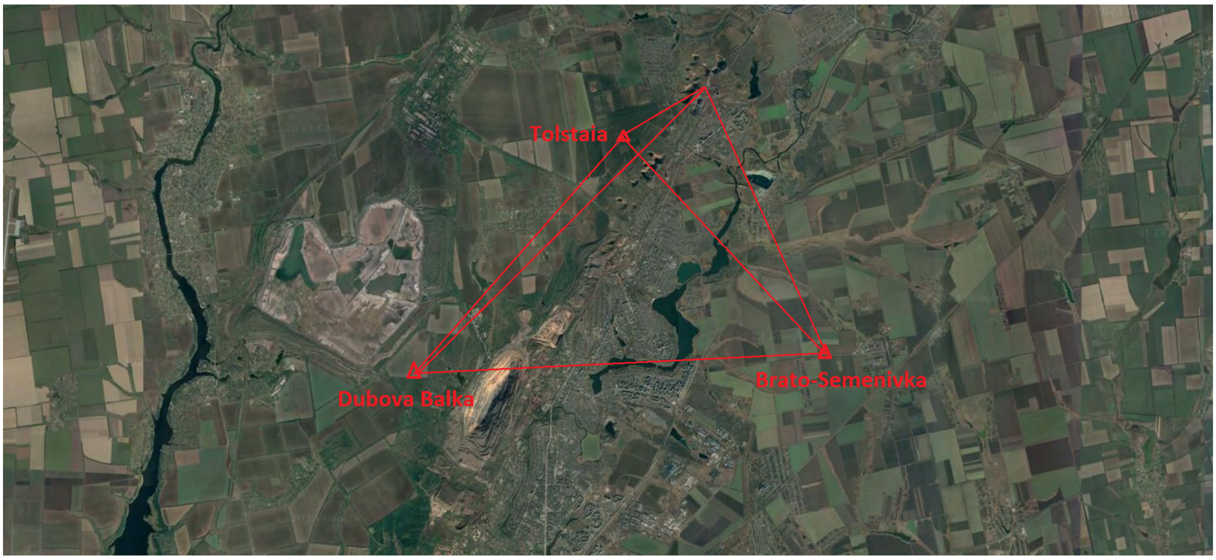

Figure 2. Scheme of linking to triangulation points.

This scheme to locate the benchmarks allowed us to make the determinations on the respective profile lines more accurately.

3. Analyzing the research results

Based on the results of the research, the following results were obtained:

- using the method of observation stations, the marks of the references were obtained based on the leveling data, and the results of linear and angular measurements
- the location in plan benchmarks and the distance between them;
- the results of instrumental surveys made it possible to refine the design data of the project organizations and make adjustments to the project decisions;
- the information obtained on the current technical and geomechanical state of the ground surface and other objects located in the study area allows us to provide a short-term prediction for a particular period;
- the results of the work allow us to clarify the parameters of the displacement zone and its location;
- the effective use of modern satellite methods in conducting instrumental measurements on profile line benchmarks has been proven.

It is known, the analysis of deformation values obtained at the points of location of the benchmarks and characterizing the deformation processes of the earth's surface and individual buildings is performed to analyze the state of the ground surface and buildings located on it. The analysis is carried out taking into account the values of critical deformations characterizing the process and used to determine the boundaries of the zone of dangerous influence of underground works and shear angles. It is known that the values of critical deformations are as follows:

- curvature k $-0.2 \cdot 10^{-3}(1/m)$;
- inclination i $-4.0 \cdot 10^{-3}$;
- horizontal tension-compression ε $-2.0 \cdot 10^{-3}$.

Figure 3. Schematic of the location rappers, the position determined by the satellite method.

Depending on the conditions of the research, different methods are used, including traditional ones: linear-angular measurements, notches, etc. In order to study the impact of mining on the building and its territory, 12 soil and 10 wall replicas were laid on the territory of the kindergarten (figure 4).

The chosen methodology for monitoring deformations makes it possible to determine the horizontal and vertical displacements benches, in accordance with DSTU B V.2.1-30:2014, according to the II class of measurement accuracy.

To reduce the risks to the safe exploitation of buildings and structures, an additional photogrammetric control method is performed.

At the same time, the ground survey is carried out with a digital camera from high points of the location, and the aerial survey is carried out from an unmanned aerial vehicle.

In figure 5, the area studied by aerial survey is circled in green, and the area studied by ground digital survey is circled in red. For aerial surveys, the SENSEFLY EBEE unmanned aerial vehicle is used, and for ground stereo surveys, a Canon EOS 6D Mark II camera and a Topcon Hiper Plus satellite receiver. The aerial survey covers almost the entire territory of the

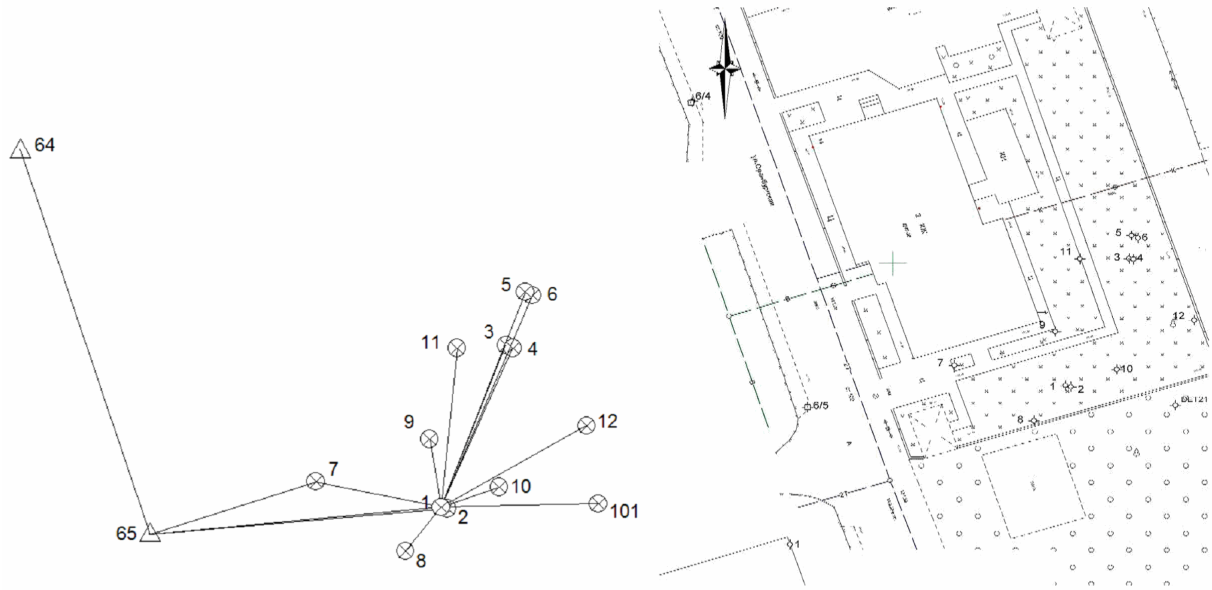

Figure 4. The location of the observation station's benches on the territory of the kindergarten.

mine's mining allotment.

Aerial photography is effective remotely monitoring areas that are dangerous for humans, such as landslide zones [16–19]. However, with a sufficiently high efficiency of photogrammetric remote methods, there are disadvantages, which consist in the impossibility of detailed marking and coordination in the landslide zones, the presence of vegetation and significant elevation differences, which complicates the survey process.

It is proved, automated method of comparing point clouds obtained for two digital models can have significant errors, and differences in determining the positions of points that can reach 10-15 meters [20]. Therefore, after the primary processing and determination of image orientation elements, further processing is performed in Delta/Digitals software.

In the case of setting pickets and other points along the upper and lower borders using a stereoscope, the mark in the "manual" mode can be brought closer to the ground surface, which, unlike the automatic mode of creating and comparing point clouds, will not allow building surfaces on the tops of trees and vegetation, which are false.

The methods of automatic detection and "surface level selection" for such objects don't work because of the complex terrain and significant elevation fluctuations. Manual pickets take much more time when performing cameral work, but provide an accuracy of 0.1-0.2 m, rather than 10-15 m, as with automatic. Figure 6 shows the distribution of deformation values in the experimental area in millimeters by color.

4. Features of digital surveying

Ground stereotyping is performed by a Canon EOS 6D Mark II digital camera with a set of lenses [21–23]: Canon EF 50mm 1:1.8II, Canon Lens EF 50mm 1:1.4 and Sigma 85mm 1:1.4 DG HSM. If you need to get more detailed images, you can use the Phoenix AF 2x teleconverter, which is inserted between the camera and the lens and doubles the focal length of the lens, which allows you to zoom in on a larger scale, bringing the subject much closer. However, the disadvantage of using a Tele-converter is that the focusing time is almost three times longer.

Figure 7 shows images of the slope of the embankment area with the remains of the building, obtained with lenses with focal lengths of 500 mm and 50 mm, respectively. The 500 mm

Figure 5. Location ground and aerial surveys.

MTO 500 lens was used in conjunction with the Canon 1200D. When switching to a full-frame camera, the Canon EOS 6D Mark II, work with the MTO 500 is impossible due to hardware incompatibility.

Based on the results surface survey, a comparative analysis of the two surfaces constructed from the images was performed and a color image to distribute the deformation values researching areas during the period between surveys was created (figure 8).

The color image of deformations, as shown in figure 8, allows you to visually assess the condition of a surface or object and helps to make timely decisions on taking the necessary measures to protect the environment and buildings and structures [22–24].

In 2022, the “Methodology for inspecting landslide zones by color display of deformation values” by O. V. Dolgikh, under the agreement between Kryvyi Rih National University and the Private Joint Stock Company “Central Iron Ore Enrichment Works”, was put into production and showed its effectiveness in studying deformations in difficult and dangerous conditions.

The survey is performed using a special application that combines a digital camera and a Topcon HiperPro satellite receiver (figure 9) [24].

The research results are presented in tabular and graphical form. The tables, in accordance with the requirements of the instruction [25–27], show the estimated values of vertical and horizontal deformations, subsidence slump for different time periods: from the date of the beginning of measurements or from the last measurements. The graphical display of the

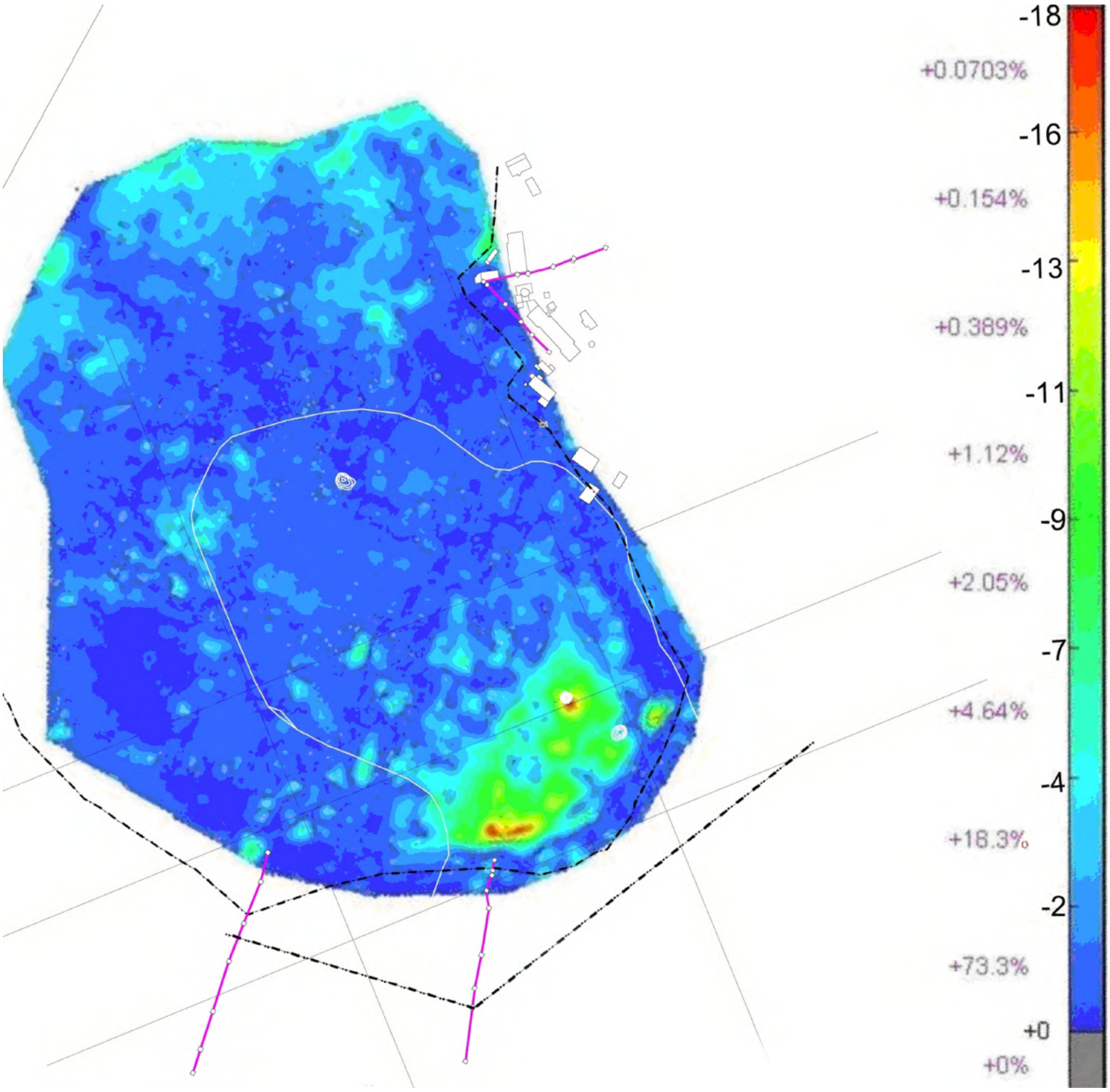

Figure 6. The results researching of the surface condition based on the data of aerial photography.

deformation values allows us to visually present the results of the monitoring (figure 10).

The research made it possible to determine the values of deformations on the benches of the profile lines observation station and, taking into account the planned mining activities, to predict the further state of the landscape and objects.

Figure 10 is a graph of subsidence of benchmarks 15, 19 and 20 for the measurements period from 2012 to 2023.

The research made it possible to determine the values of deformations benchmarks of the profile lines of the observation station and, taking into account planned mining activities, to predict the further state of the area and objects. The results of a comprehensive study of the landslide and deformation process, using satellite methods and photogrammetric methods using aerial and ground surveys, made it possible to more reasonably determine the number of voids

(a)

(b)

Figure 7. Images obtained: (a) – with a focal length of 500 mm (Canon 1200D + MTO 500); (b) – with a focal length of 50 mm (Canon 1200D+ Canon Lens EF 50 mm 1:1.4).

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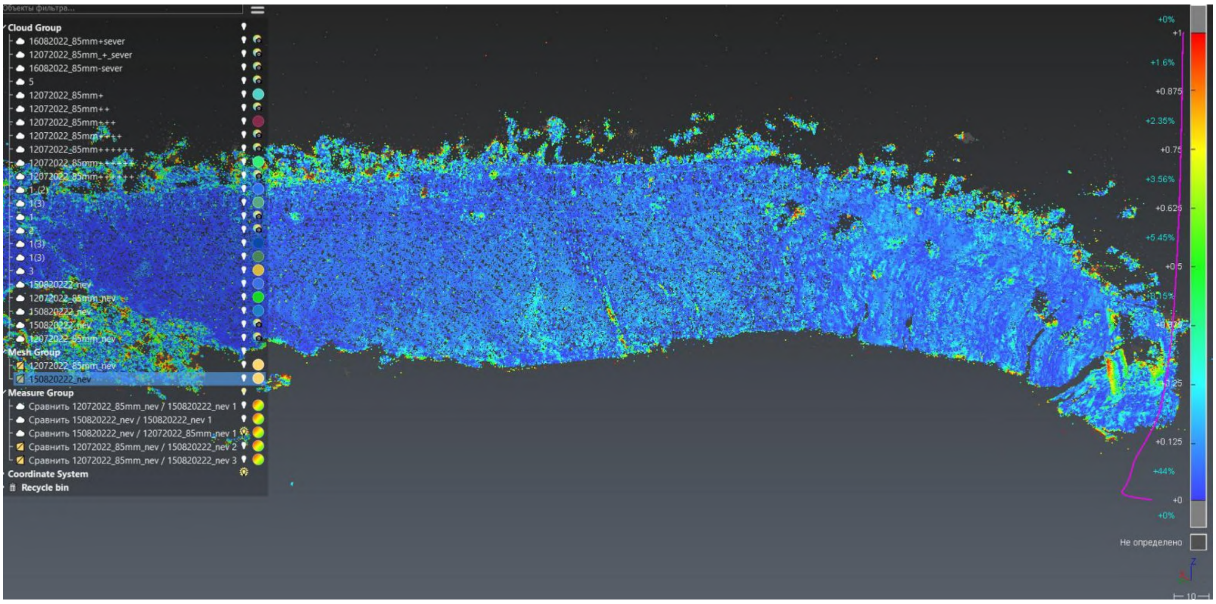

Figure 8. Schematic of the location rappers, the position determined by the satellite method.

Figure 9. Schematic of the location rappers, the position determined by the satellite method.

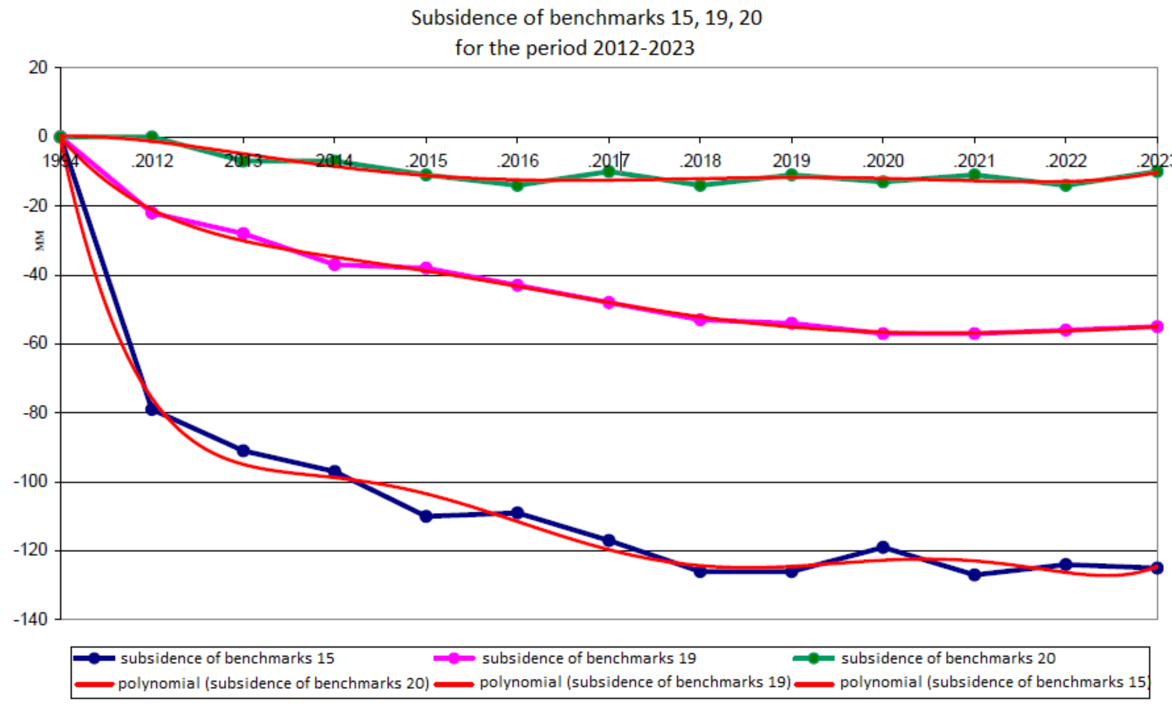

Figure 10. Schematic of the location rappers, the position determined by the satellite method.

filled, to obtain a complete characterization of the study area, which allows to improve the safety of buildings and structures located in areas affected by underground mining operations. Based on the analysis of the instrumental measurements performed in the study area, it was found that the actual size of the landslide hazard zone in 2023 does not exceed the design one, and the deformation processes are attenuated on the profile lines of the hanging face of the deposit.

5. Conclusion

The research negative influence mining activities on the environment is an urgent problem throughout the entire life of a mineral deposit. The use of the most modern technologies in performing instrumental measurements and processing the data obtained allows to increase the efficiency of these works, which affects the reliability of the forecast of the future state of the area and objects. The studies have proven the advantage of digital imaging of objects and the daytime surface in conditions where it is dangerous for a person to be on them. The use of satellite technologies allows obtaining a more complete analysis of the deformation process in conditions where simple distance measurements and leveling doesn't provide complete information about the process. The important goal of the surveying service of a mining enterprise is researching the impact of mining activities on the environment, which today requires further research to improve it [19].

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Methodology of operative setting of mass crystallization parameters of gas hydrate in reservoir systems

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Methodology of operative setting of mass crystallization parameters of gas hydrate in reservoir systems

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Abstract. In the course of experimental studies, the method of operational setting of the parameters of mass crystallization of gas hydrate in reservoir systems that have not reached a state of equilibrium is substantiated. The technique is implemented by setting the process parameters at the moment of visual identification of the solid phase of the gas hydrate on the interphase surface of the gas bubble or the place of its exit from the liquid. The requirements for the construction of the reactor unit of the laboratory installation for the implementation of this technique are substantiated. A laboratory installation has been developed and implemented. The results of test studies are presented and the features of identification of the solid phase of gas hydrate at the moment of the beginning of its mass crystallization are demonstrated. The proposed method allows you to quickly obtain objective information about the possible behavior of this system in the case of intensive changes in parameters in non-equilibrium conditions.

1. Introduction

The course of any technological process requires control of its parameters. This is especially true for the oil and gas industry. As is well known, the production of hydrocarbons is accompanied by the formation of undesirable solid clathrate structures – gas hydrates [1, 2]. In this regard, there is a need for constant and operational monitoring of hydrate formation parameters in production and product preparation systems (where there are thermobaric conditions favorable for this) [3].

Along with that, the thermobaric parameters of a significant part of the technological chain of extraction and preparation of hydrocarbons lie in a narrow range of equilibrium conditions of hydrate formation. Moreover, system parameters can change constantly and quite dynamically. However, even their slight fluctuation can stimulate the formation of gas hydrate, its dissociation, and further – repeated hydrate formation [1, 4]. Based on this, these processes definitely need constant support in the form of operational monitoring of their parameters. However, the considerable duration of laboratory setting of parameters of hydrate formation according to traditional methods [5] often does not allow to do it quickly enough. In addition, in order to effectively control the technological process, it is necessary to have means of operational prediction of the behavior of the system at any point of the technological chain. However, classical methods provide for fixing the equilibrium parameters of hydrate formation at the moment when the system reaches equilibrium [5, 6]. At the same time, in most cases, the speed of fluid flow in technological lines and the dynamics of changes in its parameters in no way allow the system to reach an equilibrium state. Therefore, it is important to promptly predict the behavior of the system under the condition that it is guaranteed to be in an unbalanced state and will not be able to reach it during the time of movement along the technological line.

Thus, the goal of the work is to develop a methodology (and appropriate equipment) for quickly setting the parameters of mass crystallization of gas hydrate in reservoir systems that have not reached a state of equilibrium, as well as to substantiate the design of a laboratory installation for its implementation.

2. Features of formation of gas hydrates

Gas hydrates are non-stoichiometric crystalline compounds that are formed at relatively low temperatures and a certain pressure [1].

There are three main stages of phase transitions associated with the formation of gas hydrates: nucleation, growth, and agglomeration [1, 7]. The formation of gas hydrate is a phase transition of the first kind, which begins with hydrate nuclei (crystal nuclei) [8]. The process of hydrate nucleation is preceded by a time interval during which the "water – gas" system is in a metastable state, which is called the induction period. This time is necessary for the formation of a certain amount of the hydrate phase or absorption of the hydrate-forming gas. In this process, hydrated shells and clumps of particles (their aggregates) grow and decompose. Nuclei must reach a critical radius before further growth becomes thermodynamically advantageous [9]. The formation of embryos is stochastic and not yet fully explored. Stochastic behavior increases with decreasing sample volume [10] and system supercooling [11].

The process of gas hydrate formation is surface-contact. Experiments [12] and simulations [13] show that, due to the low solubility of hydrocarbons in water, the formation of nuclei mainly occurs at the interphase boundary, where both hydrate components are present.

Nucleation can be induced through crystal nuclei or can occur spontaneously through random molecular interactions [14]. In the case of spontaneous nucleation, the energy barrier (Gibbs energy, Δ G) must be over come for the formation of critical nuclei. The probability of this will increase with the growth of the driving force of the phase transition [15]. This driving force is determined primarily by the degree of supercooling (Δ T). However, in the case of gas hydrates, it also depends on pressure, temperature, gas composition and degree of supersaturation [1]. At a given pressure, the driving force of the process is the supercooling temperature, which is the main characteristic of the hydrate system and can affect the induction time [1, 9].

The rate of nucleation depends significantly on the thermal history of the system. This phenomenon is called the memory effect [16]. A solution that previously contained hydrate or ice and was kept at a low temperature shortens the time of nucleation [16]. However, when the dissociation temperature was higher than 25 $^{\circ}C$, the memory effect disappeared [17]. This fact is explained by the fact that water has a kind of structural memory and the crystal structure that existed before the melting of ice or hydrate remains as structural elements in liquid water. These structures combine again in the presence of gas molecules and form critical hydrate nuclei [1, 2].

After reaching the critical size of the nuclei, the stage of mass crystallization follows. Crystal growth occurs by diffusion and inclusion of blocks on the critical surface of the nucleus. This stage is spontaneous and is accompanied by a sharp increase in gas consumption [1, 2].

As in the case of nucleation, the main site of hydrate growth is the interfacial surface. Under static conditions, the hydrate spreads and occupies the entire free surface of the "water – gas" contact, forming a hydrate film on it. Further hydrate growth is determined by the diffusion of water and gas to the front of hydrate formation through the hydrate crust [1, 2].

In the case of mechanical interaction of crystals, their agglomeration is possible – a stage of phase transition resulting in the formation of hydrated plugs [2].

3. Methods of setting hydrate formation parameters

Despite the achievements in the study of the properties of gas hydrates, significant practical experience in their prevention, scientific innovations and technical improvements, the problem of combating such complications remains relevant. Therefore, reliable and economical hydrate management strategies have become an urgent need for safe and reliable oil and gas production. Important components of these strategies are the development of methods to detect early signs of hydrate formation to give operators sufficient time to take appropriate measures to prevent hydrate formation.

In recent years, new technologies have emerged to provide the necessary information to field operators to understand how thermodynamically close the system is to hydrate formation conditions, known as gas hydrate early warning and monitoring systems. It is believed that various analytical methods together with experimental simulations from large-scale to micro-scale will play an important role and provide strong support for future research on gas hydrates [18].

In general, the equilibrium of the hydrate phase in the presence of pure water or solution can be predicted relatively accurately with existing software. Existing models for predicting the phase equilibrium of hydrates are mainly proposed based on the Van der Waals and Platteu model [19]. However, a large amount of experimental data is still needed to validate the models. In particular, the predictions of some models are very sensitive to experimental data.

There are several experimental methods for determining the parameters of gas hydrate phase equilibrium, for example, the visual control method, the graphical method, as well as a number of the latest technologies that require special equipment [5]. An observation method is also used, which requires a transparent reactor and is only suitable for solution systems. The graphic method is the main one. It is divided into isothermal, isobaric and isochoric (consists in keeping one of the three parameters constant) [5]. Among them, due to its simplicity, the isochoric or T-cycle method is widely used [20]. In this method, the temperature of the system is gradually reduced, ensuring the formation of hydrate, which is detected by the pressure drop in the vessel and/or by visual observation. After the hydrate is formed, it is dissociated by heating. On the corresponding "pressure – temperature" diagram, the intersection of the cooling and heating paths is considered as a point of thermodynamic equilibrium [6]. The conditions for the formation of hydrates have a greater degree of dispersion compared to the conditions for dissociation. Therefore, it is advisable to fix the hydrate equilibrium at the stage of dissociation. Two methods of heating are used: continuous (with a rate of about 0.2 K/h) [6] and stepwise [21] (for example, with a step of 0.5 K and a duration of 4-8 hours). Thus, the determination of only one equilibrium value of gas hydrate dissociation takes 24-48 hours.

Since measuring a wide range of equilibrium thermobaric parameters and concentrations is a time-consuming and expensive process, it is possible, as mentioned above, to use reliable models [22] or software for their prediction.

However, when the system contains gaseous mixtures or an aqueous solution of organic inhibitors, some methods are imperfect, which requires more accurate experimental data [22]. Moreover, simulations may not predict metastable states occurring under certain thermodynamic conditions that may be common in hydrate reservoirs [23]. Therefore, experimental determination of hydrate formation parameters is still relevant.

4. Justification of the need for operational control of gas hydrate mass crystallization parameters for systems in non-equilibrium conditions

The result of the manifestation of the water memory effect is a significant discrepancy in the results of experimental studies. However, based on the analysis of technological processes, the maximum temperature of part of the production wells and most of the intervals of the well product preparation lines does not exceed 18-20 $°C$, that is, much lower than the temperature of the destruction of the structures that determine its memory (about 30 $°C$ [17]). In addition, in addition to water, well products include dispersed solid phase impurities of various nature (gas hydrate crystallization centers). Thus, the induction period, with repeated hydrate formation, in such a system will be absent or its duration will be insignificant.

Given that reservoir systems are constantly in a non-equilibrium state after production, in the laboratory determination of the probability of the formation of a solid phase of gas hydrate there is no need (or it will be a mistake) to wait long before fixing the result.

In addition, taking into account the intensive change of thermobaric parameters of real systems, in order to reduce the duration of their laboratory research (process modeling), it is advisable to provide an increase in the speed of their change by 1-2 orders of magnitude (for example, up to 0.1-0.3 $°C/\mathrm{min}$).

At the same time, the investigated parameters that must be taken into account for controlling the technological process should be the thermobaric parameters of repeated mass crystallization of the gas hydrate and the duration of its delay, as well as the parameters and rate of gas hydrate dissociation.

As is known, one of the conditions for the formation of gas hydrate is the presence of a condensed phase of water [1]. At the same time, its composition may contain a significant amount of microcrystals of gas hydrate. But their presence in the reservoir system does not harm the process until a certain point. So in the work [24, 25] the parameters are substantiated and the possibility of pumping and movement through the pipeline without complications of gas hydrate suspension in water is demonstrated.

But after some time, crystals may thicken through their growth and/or coagulation, or their dissociation (but mainly preservation of elements of hydrate structures that provide (so-called) memory properties of water). The process is accelerated by changing thermobaric conditions. At the same time, it is important to set the parameters of the process at the moment of the beginning of the consolidation of gas hydrate crystals (the stage of their massive growth).

Thus, for the effective control of a number of oil and gas production processes, it is important to quickly (in the order of minutes) laboratory determination of mass crystallization parameters of gas hydrate nuclei in reservoir systems under non-equilibrium conditions.

5. Justification of the principle scheme of the laboratory installation

5.1. Optical system

Currently, a wide variety of phenomena and processes can be studied using microscopy methods combined with image capture and processing technologies. This technology allows detecting earlier stages of processes. Therefore, the thermobaric parameters recorded at the moment of visual identification of gas-hydrate structures will be sufficiently accurate even when using budget laboratory equipment. Therefore, it is advisable to use the method of visual control of the sample as the main source of information in the research methodology of the mass crystallization process of gas hydrate.

The use of a microscope in the optical system of a laboratory setup involves the study of a small object or reactor volume. Based on this, the reactor of the laboratory installation can be of minimum size. Also, obtaining a high-quality image of objects requires their high-quality lighting. In this case, the light sources must be placed in such a way that transparent and colorless hydrate crystals "appear" as clearly as possible on the obtained images.

5.2. Mixing system

Intensification of hydrate formation involves the creation of maximum "gas – liquid" interphase contact. For this purpose, reactors are equipped with devices for mixing. The use of a small-volume rector requires analysis and optimization of the mixing system. For example, effective contacting of phases can be achieved in the process of intensive gas bubbling through a liquid layer.

When bubbling, gas bubbles are pushed to the surface. Moving through the liquid layer, they cause its turbulent mixing, and therefore relatively developed interphase interaction. At the exit from the liquid, the bubble overcomes the interaction forces of the surface layer at the interfacial contact, causing a short-term disturbance.

In addition, the very process of bubble growth (and therefore the area of interfacial contact) at the opening of the bubbling device is actually a process of mixing on the scale of the liquid surrounding the bubble.

Thus, the periodic process of bubble nucleation, its growth, detachment after reaching a critical size, movement through a layer of liquid and disturbance at the moment of breakthrough of the "liquid – gas" contact can be considered as a process of mixing the local volume of liquid in the reactor with a mini-mixer of the bubbling type.

At the same time, the composition of the gas phase in the reactor will change during the formation or dissociation of the gas hydrate. In the work [26] shows a monotonous change in gas composition during each operation. Therefore, the advantage of bubbling mixing (if the gas is supplied from outside and not circulated in the system) is that each bubble is a portion of gas whose composition has not undergone previous changes as a result of selective dissolution or hydrate formation.

Therefore, in the design of the laboratory installation, it is advisable to provide:

- small volume reactor;
- an optical system based on a microscope;
- a device for bubbling mixing of reactor contents.

Therefore, when using bubbling mixing, the most informative objects for recording the signs of mass crystallization will be gas bubbles and the liquid surface in the zone of their exit. Considering the focal length of the microscope, the object must be in close proximity to the transparent window of the reactor. Since gas hydrate crystals can form both on the bubble and on the surface of the liquid in the reactor, the entire picture of the process must be in the field of view of the microscope. Therefore, it is advisable to place the reactor in such a way that the plane of contact "liquid – gas" is roughly half a transparent window. (In the version of the rector of a cylindrical shape with an end viewing window - orient in a position close to horizontal.)

Structurally, slow gas bubbling and the possibility of visual control of the processes on the surface of the bubbles and the place of their exit are proposed to be implemented with the help of a single capillary immersed in the liquid near the viewing window. For improve observation of the bubble, it is suggested to place the capillary below the liquid level in the reactor at an angle of 20-30 ° to the horizontal. In addition, close the lower opening of the capillary and cut an oval on the side (figure 1). A bubble that stays on the opening of the capillary for a certain time is formed as a result of the ultra-sensitive balancing of the surface tension forces, the pressure of the liquid column and the gas pressure in the capillary with minimal gas supply.

The fact of the appearance of the solid phase of the gas hydrate is proposed to be recorded in this microvolume (which is approximately 3-5 ml). For such a volume, this method of mixing will be sufficient to quickly approach the concentration of gas molecules in the liquid to equilibrium. According to previous studies, the intensity of bubbling to saturate the liquid with gas is assumed to be within 0.5-3 bubbles per minute.

In the design of the reactor of the laboratory installation, it is also advisable to provide an auxiliary rotary mixer for mixing the entire sample. For example, without interfering with the research, control the effectiveness of microbubble by periodically turning it on. At the same time, the stirrer blades must effectively bubble gas bubbles into the liquid and disperse them. In the course of previous studies, the best result (recorded by increasing the temperature and

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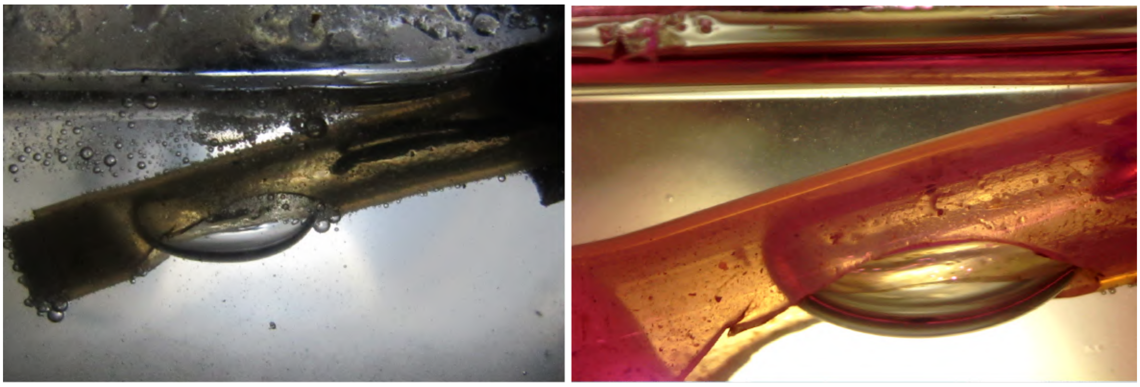


Figure 1. The formation of a gas bubble at the opening of a capillary immersed in a liquid (photo by the authors in the process of research).

Figure 2. Rotor of a mechanical stirrer.

decreasing the pressure in the reactor) was noted for the design of the mixer rotor shown in figure 2 in the horizontal arrangement of its axis.

In this position, the stirrer blades move part of the way in the gas phase during rotation. Then they plunge into the liquid, cutting its surface, and capture a certain volume of gas. Next, this gas is dispersed to the size of microbubbles. At the exit from the liquid, the agitator blades pick up part of the liquid and disperse it. As a result, almost immediately after turning on the stirrer, the sample under study turns into a foamy mass that fills the entire volume of the reactor (figure 3). This allows for 3-5 seconds of operation of the rotary mixer to bring the system as close to equilibrium as possible.

5.3. Improvement of the pressure and temperature control system

During the tests of the laboratory installation, a significant sensitivity of the capillary system to the pressure drop between the reactor and the gas supply line was recorded. So, for example, after cutting off the reactor volume with a valve located along the inlet line at a distance of 15 cm and the stirrer running for 2 s, the active release of bubbles from the capillary was recorded. At the same time, the phase shift of mixing and the release of bubbles occurred within 1 s. After repeated turning on of the stirrer, bubbles did not appear. The reason for equalizing the pressure between the reactor volume and the capillary line was stimulation of the dissolution of gas molecules in the undersaturated liquid. In another case, 1.5 min after the start of the stage of intensive heating of the sample (heating inertia was observed), the liquid began to rise

a *b* *c*

Figure 3. The position of the rotor of the stirrer in the reactor (a) and the appearance of the test sample during the operation of the stirrer (b) and after its stop (c) (photo by the authors during the research).

through the capillary. Therefore, in addition to the function of a bubbling device, a capillary immersed in a liquid can be periodically used as a super-sensitive differential manometer during research to assess the pressure change between the reactor and the gas input line.

For increase the sensitivity of this differential pressure gauge on the gas supply line, it is advisable to sequentially place a fine adjustment valve and a buffer tank (receiver) with a volume of 30-50 ml. After overlapping the input and output lines, a system of two containers is formed, connected to each other by a capillary line with a hydraulic valve of the liquid layer. As a result, any decrease in pressure in the reactor (as a result of temperature decrease, gas dissolution or hydrate formation) will be accompanied by the release of bubbles at a rate proportional to the intensity of the process.

In the course of preliminary testing of this system, it was established the need to experimentally select a certain level of thermal insulation of the buffer tank: more intensive gas cooling in it compared to the reactor leads to liquid being pushed from the reactor into the tank, and excess thermal insulation leads to too intense bubbling of gas during the research process.

For increase the sensitivity, it is advisable to place the temperature sensor in the liquid phase as close as possible to the capillary system, but distance it on a heat-insulating support from the metal body of the reactor.

At the same time, at the moment of mass crystallization of gas hydrate in the reactor, its minimum amount is formed. This practically makes it impossible to fix the temperature anomaly of this endothermic process.

5.4. Identification of signs of the solid hydrate phase on the interfacial surface

As is known, the process of hydrate formation occurs most intensively at the interphase boundary and is visually manifested after a certain induction period from the moment of mass crystallization in the form of a hydrate film. Visually, this process is fixed by the transformation of the mirror surface of the interphase boundary into a matte one. In addition, in the course of research, it was established that the most effective sign of the formation of microcrystals of gas hydrate on the surface of the bubbles is the distortion of the reflection of the light source on it. The dynamics of the mass crystallization initiation process is illustrated in figure 4.

As can be seen in figure 4, b and figure 4, c, no other visual signs of the beginning of the process of hydrate formation (mass crystallization) are observed, except for the distortion of the reflection of light sources on the surface of the bubbles. At this stage, it is extremely difficult

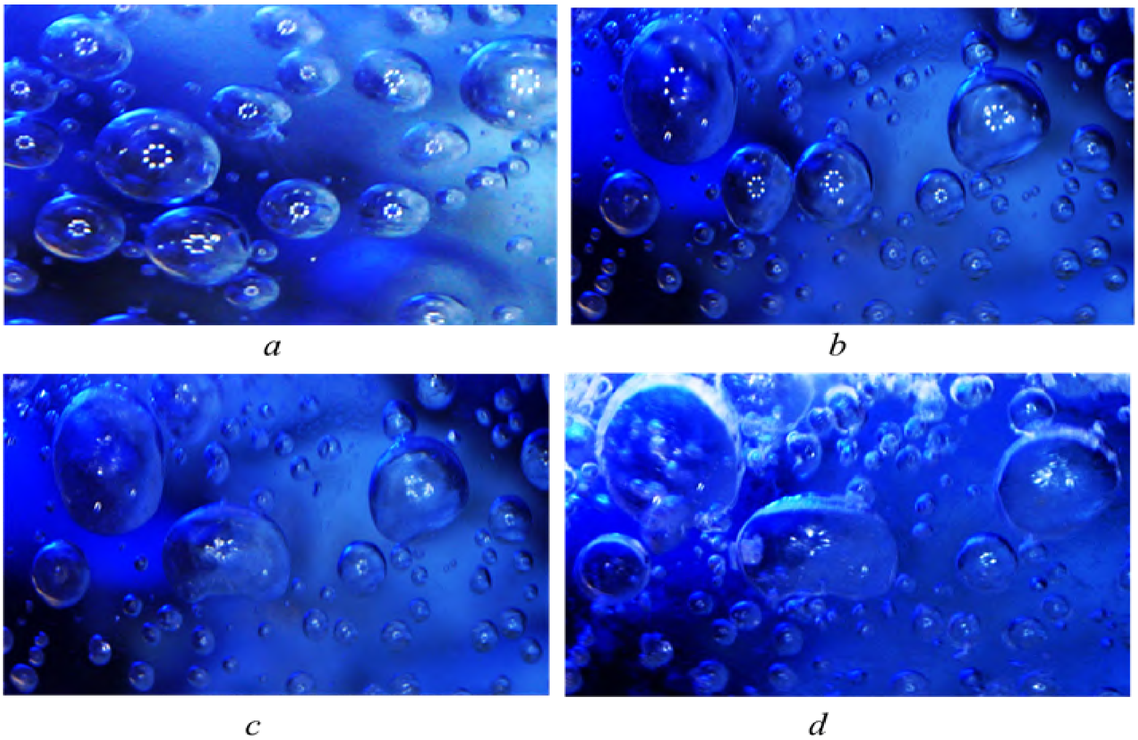


Figure 4. Dynamics of distortion of reflections of point light sources on the surface of gas bubbles as a result of the formation of a film of gas hydrate crystals (photo by authors in the process of research): a – the reflection is clear, without distortions; b – the first visual signs of reflection distortion (formation of a gas hydrate solid phase); c – significant reflection distortion (mass crystallization); d – the surface of the bubble becomes matte due to the formation of a thick crust of gas hydrate.

to record the change in thermobaric parameters in the reactor.

6. Design features of the laboratory installation

Taking into account the above, it is possible to formulate the following basic requirements for the design of the reactor unit of the laboratory installation for the implementation of the method of setting the parameters of the start of mass gas hydrate crystallization:

1) the shape of the reactor is cylindrical, the ratio of its diameter to length is within 1x2.5-3.5, the diameter of the reactor is within 45-65 mm;
2) the position of the reactor is horizontal or close to horizontal (it is necessary to provide for the possibility of adjusting the angle of inclination of the rector);
3) the presence of a rotary mixer whose shaft axis coincides with the axis of the reactor;
4) the level of optimal filling of the reactor with liquid relative to the viewing window is within 50-60 %;
5) the presence of a fine adjustment valve on the gas input line to the reactor with a flow rate starting from 1 bubble per 3 minutes;
6) placement of the capillary system: a transparent capillary with an inner diameter of 2.5 mm is placed in the liquid at an angle of 20-25° to the horizontal;

7) the following research objects should be within the visual range of the optical system at the focal distance: a gas bubble at the opening of the capillary, a part of the surface of the liquid in the reactor where the bubble breaks through to the surface, and a layer of liquid between the opening on the capillary and its surface. Taking into account the possible different light transmittance of the investigated systems, the thickness of the glass of the observation window and the limited focal length of the microscope of the optical system, the capillary must be placed at a minimum distance from the observation window, and it should be oriented in such a way that the trajectory of the bubble after separation is between the capillary and the glass. Thus, the hole on the capillary should be 15-20 mm below the axis of the reactor, but at least 5 mm from the reactor body and 4-6 mm from the viewing window. Based on the thickness of the transparent window of the reactor and the size of the controlled zone, the level of magnification by the optical system will be in the range of 70-120;
8) to obtain a high-quality image, it is necessary to place a light source behind the investigated object. A variant of such a source for an opaque reactor, in the form of a system of an external light source and a cylindrical crystal with a hemispherical end for scattering light, mounted in a through hole in its wall, is presented in figure 5;
9) from the outside of the reactor at a minimum distance from the axis of the microscope lens, it is necessary to place an auxiliary light source, but in such a way that the reflection from it on the surface of the window does not distort the image figure 6;
10) place an intermediate heat-insulated container with a volume of 0.5-1.5 reactor volumes along the gas supply line between the shut-off valve and the reactor.

Taking into account the requirements for the design of the reactor unit of the installation for the implementation of the methodology for setting the parameters of mass gas hydrate crystallization, a laboratory installation was developed and manufactured, the diagram of which is presented in figure 7. In figure 8 a photo of the reactor unit of the installation and its elements is presented.

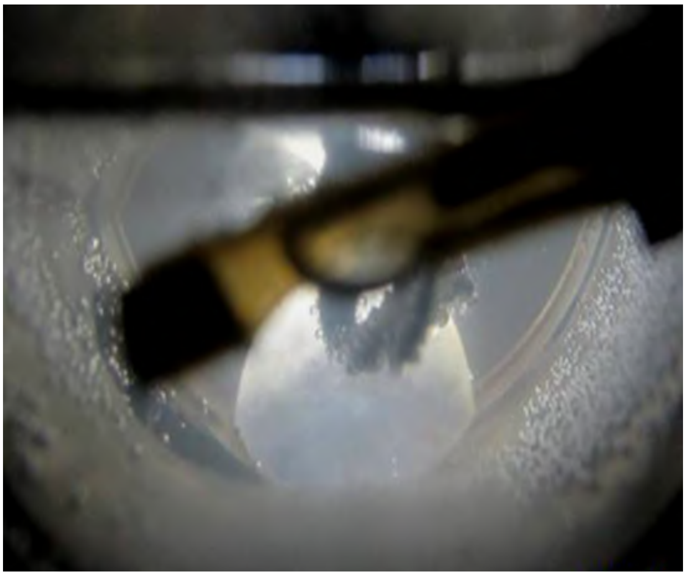


Figure 5. Source of scattered light in the reactor (photo of the authors in the process of research).

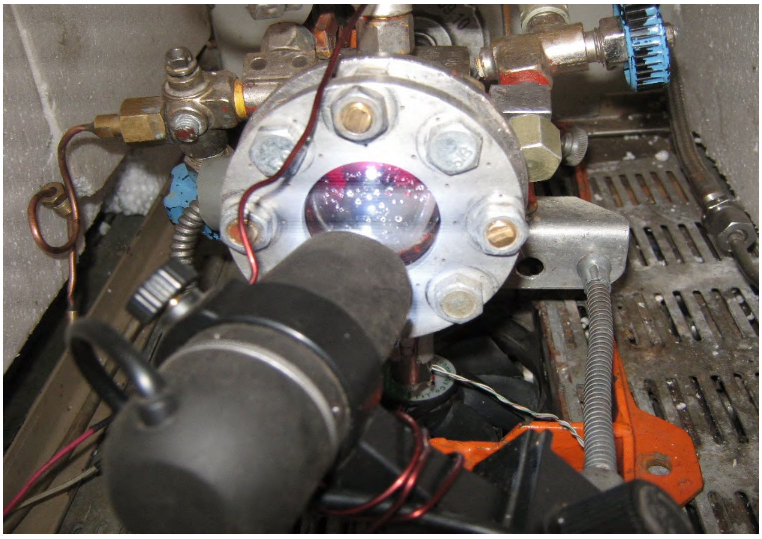


Figure 6. An example of the use of auxiliary lighting of the reactor viewing window (photo of the authors in the process of research).

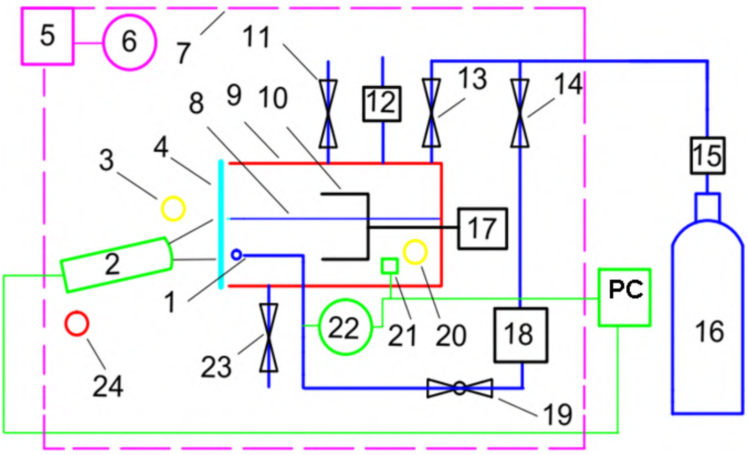


Figure 7. Schematic diagram of a laboratory installation for the implementation of the method of setting parameters for the start of mass gas hydrate crystallization: 1 – bubble capillary; 2 – optical system (microscope); 3 – external light source; 4 – observation window; 5 – refrigerating unit; 6 – fan of the thermostatic unit; 7 – thermal chamber; 8 – liquid level in the reactor; 9 – reactor body; 10 – mixer rotor; 12 – safety valve; 13, 14, 23 – valve; 15 – reducer; 16 – gas source; 17 – mixer drive; 18 – thermally insulated buffer capacity; 19 – valve for fine adjustment of gas supply; 20 – reactor lighting system; 21 – temperature sensor; 22 – manometer (pressure sensor); 24 – heating element; PC is a computer.

7. Preliminary experiments

In the course of research, it was established that the most favorable conditions for the beginning of mass crystallization (appearance of visual signs of the solid phase) occur in the zone of exit of the bubble to the surface of the liquid (figure 9, a), along the perimeter of the capillary opening (figure 9, b) and in the lower "pocket" of the capillary (figure 9, c). In the first case, the most active mixing takes place in this area, in the second and third – cyclic wetting of the capillary walls 1 (figure 7) with a water film, that is, the formation of a new interfacial contact surface. At

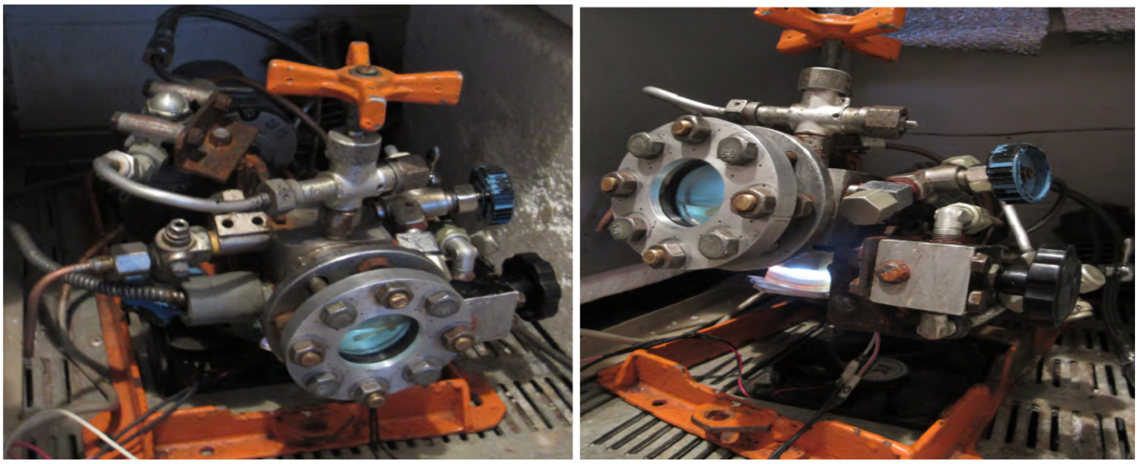
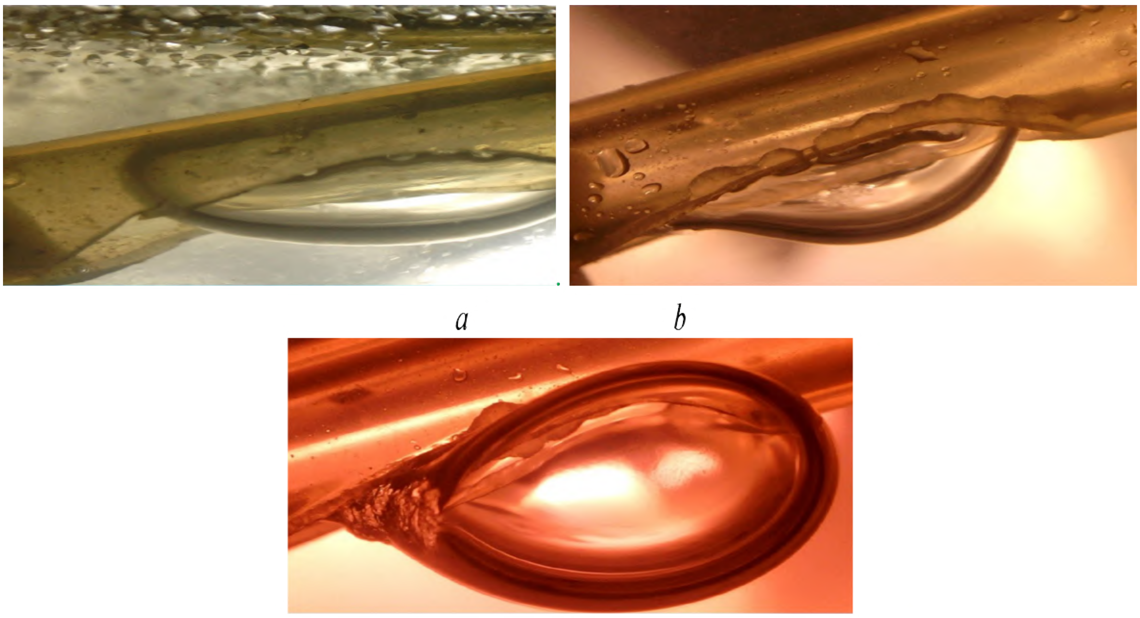


Figure 8. Photo of the laboratory installation (photo of the authors in the process of research).

the same time, most often the first signs of the solid phase of the hydrate were recorded in the zone of bubbles breaking through to the surface. This is explained by the fact that, in addition to gradual bubbling mixing, the surface of the liquid in the reactor 8 (figure 7) is constantly in contact with the gas. Its molecules can be dissolved in water all the time, while the surface of the bubble exists for a relatively short time.

Thus, according to the methodology, the appearance of one of these signs is identified as the investigated moment of the beginning of mass gas hydrate crystallization under these thermobaric conditions.

The essence of the technique consists in the preliminary creation of a model of the well



a *b*

c

Figure 9. Typical signs of the beginning of mass crystallization of gas hydrate: a – in the zone of bubble breakthrough on the liquid surface; b – along the perimeter of the hole in the capillary; c – in the lower "pocket" of the capillary (photo of the authors in the process of research).

production, which has the memory of hydrate structures or the seeds of hydrate formation remain in its composition. For this purpose, at least part of the water of the studied sample is preliminarily incorporated into the composition of the gas hydrate. Next, the hydrate is dissociated as a result of a simultaneous decrease in pressure and increase in temperature. Moreover, dissociation is carried out to a level that would ensure the preservation of part of the hydrate structures and/or crystallization seeds and/or water structures that determine its hydrate memory in water.

After that, the prepared sample is subjected to gradual cooling with simultaneous gas supply to compensate for the pressure drop as a result of cooling. The gas is supplied through the capillary by the control zone. A marker of repeated hydrate formation is the formation of signs of the solid phase of the hydrate, which are visually visible at a magnification of 70-120 times. At the moment of their appearance, the corresponding thermobaric parameters are fixed.

8. Methodology

8.1. Preparatory operations

A sample is fed into the reactor 9 and vacuumed for 30 min with periodic inclusion of the stirrer 10 (figure 7). After that, the test gas is fed into the reactor. The pressure is increased to 6.0 MPa and the stirrer 10 is turned on for 10 s. After waiting for 10 minutes, the gas is released. Then the pressure is raised again to 6.0 MPa and immediately begin intensive cooling of the reactor to a temperature of 1-2 $^{\circ}C$ to achieve significant supercooling of the system. For accelerate the dissolution of the gas, every 2-3 minutes, turn on the stirrer 10 for 2-3 seconds. After the beginning of hydrate formation, the process of periodic inclusion occurs until the disappearance of the sign of gravitational water between the hydrate crystals. After that, the gas hydrate is melted. For this, the heating element 24 is turned on and the thermally insulated chamber 7 is partially depressurized. The maximum temperature to which we use sample heating in this operation and in all subsequent gas hydrate dissociation operations during the research is 16 $^{\circ}C$.

When a temperature of 9.0 $^{\circ}C$ is reached (taking into account the inertia of heating), the pressure in the reactor is reduced to atmospheric by opening valve 11 within 15-20 seconds. (The pressure in this and the following operations is reduced gradually, because when the gas is suddenly discharged, due to the small size of the reactor and its horizontal location, the liquid is removed through the fitting). After waiting for 20 seconds, valve 11 is closed. For guaranteed dissociation of the gyrate, the reactor is kept for 15 minutes until a temperature of 16 $^{\circ}C$ is reached. In further operations, the amount of hydrate will be minimal, so this exposure time will be reduced to 3 minutes.

8.2. Experiment

Before starting each repetition of the experiment, the temperature rises intensively (at a rate of 0.5 $^{\circ}C$/min) to 9 $^{\circ}C$. After that, the pressure in the reactor 9 (figure 7) decreases to atmospheric within 15-20 seconds. After holding for 20 seconds, valve 11 is closed and held for 3 minutes. An additional task of such degassing is to prevent the gradual accumulation during each repetition of C_{2+} components in the liquid phase, and therefore the associated error.

After that, depending on the repetition of the experiment, the pressure is raised to a level ranging from 1.0 to 5.5 MPa, which is approximately 0.8-1 MPa lower than the crystallization pressure. This interval is determined by the minimum temperature in the reactor during research, which for non-inhibited systems to prevent the formation of ice and the occurrence of an error in the identification of gas hydrate should not be lower than 0.5 $^{\circ}C$, as well as the maximum permissible for this reactor (7.0 MPa).

Immediately with the increase in pressure, cooling begins at a rate of 0.2 $^{\circ}C$/min. The gas input line in front of buffer tank 18, which remains connected to the reactor 9 (figure 7) through the hydraulic valve of capillary 1, is closed (valves 13 and 14 are closed and valve 19 is opened).

After that, the stirrer 10 is turned on and the process of saturation of the sample with gas is controlled by the intensity of the leakage of bubbles through the capillary 1.

By this time, the temperature in the reactor will rise to 14-15 $°C$. After reaching a temperature of 16 $°C$, a pressure of 1.0 MPa is set on the reducer 15 of the gas source 16, which is higher than the estimated one for possible gas hydrate crystallization, and the fine-tuning valve 19 is set to supply gas through the capillary 1 with an intensity of about 3 bubbles per minute. This gas supply rate compensates for the pressure drop associated with reactor cooling and slightly exceeds it. Therefore, by the time mass crystallization of the hydrate begins, the pressure in the reactor 9 will be higher than the initial one by 0.3-0.8 MPa.

When the temperature of the sample is reached, which is approximately 2-4 $°C$ higher than the mass crystallization temperature of the gas hydrate, the procedure for saturating the liquid with gas is repeated (turning on the stirrer 10 for 3-4 s). The intensity of bubbling drops to approximately two bubbles per minute. Further observation continues until the moment of fixation of signs of mass crystallization.

Immediately after that, the heating element 24 is turned on, and the above-described preparation procedure for the next repetition of the experiment continues. The results of testing the methodology on sample natural gas of a typical composition are presented in figure 10, figure 11, figure 12.

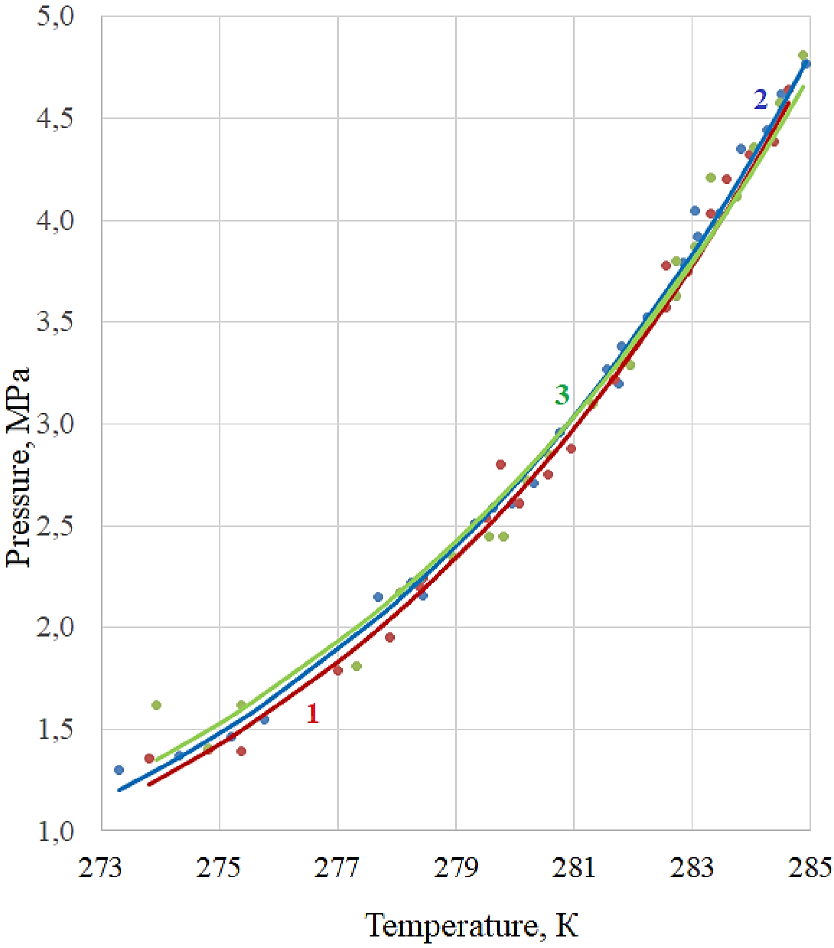


Figure 10. Results of experimental studies to establish the parameters of gas hydrate recrystallization in the studied sample: experiments 1-3.

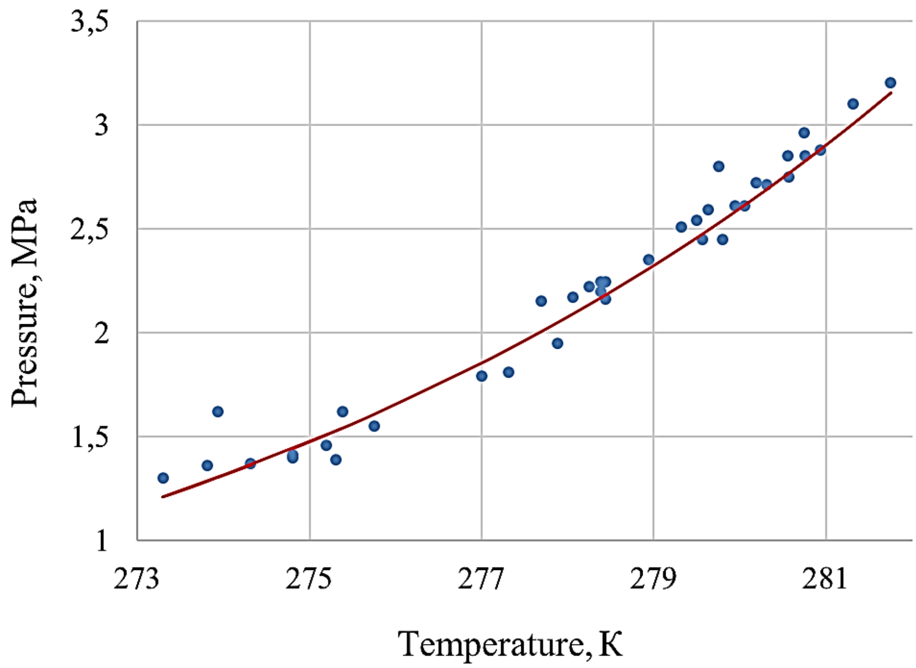


Figure 11. Approximated empirical curve of mass crystallization parameters of gas hydrate in the studied sample.

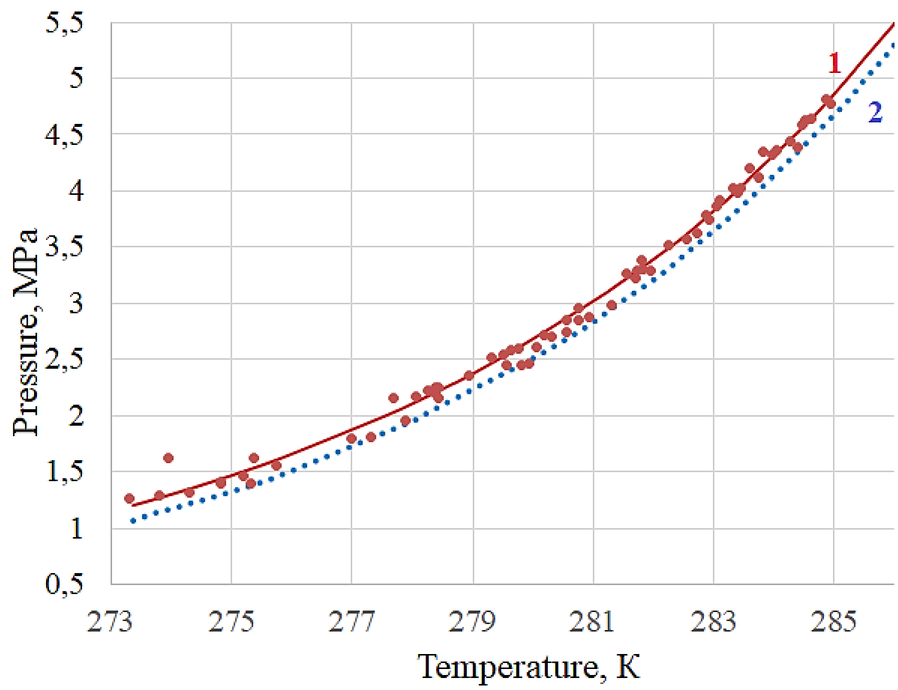


Figure 12. Comparison of the obtained experimental dependence of the mass crystallization parameters of the gas hydrate in the studied sample (1) and the equilibrium curve of hydrate formation for the given gas composition, obtained according to the Barrer-Stewart equation (2).

9. Conclusions

The method of operational setting of the mass crystallization parameters of gas hydrate in reservoir systems by visual identification of the appearance of a solid phase on the interfacial surface (on the surface of a gas bubble or at the place of its exit from the liquid during the process of increasing the pressure in the reactor and decreasing the temperature of the sample) has been theoretically justified and experimentally confirmed.

A laboratory installation was developed and implemented for the implementation of the technique of operative setting of the parameters of mass crystallization of gas hydrate in reservoir systems.

The given experimental data were obtained in less than 9 hours of the research cycle, which is almost an order of magnitude faster than the traditional methods of determining the equilibrium parameters of hydrate formation of the system.

The developed technique, first of all, makes it possible to evaluate systems that have a memory of hydrate structures. However, preliminary transfer of part of the water of the studied sample through the gas hydrate form, to give it the properties of hydrate structures, makes it possible to estimate the parameters of hydrate formation of any reservoir system.

The industrial application of this technique will allow obtaining additional important information for the prevention of gas hydrate complications. In many cases, this may be the basis for clarifying the consumption norms of hydrate formation inhibitors and the zones of their introduction into the technological line. In the course of further research, it is planned to develop samples of equipment for the implementation of this technique at industrial facilities.

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Development of a method for estimating the carbon footprint when transporting grain by road

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Abstract. The article presents the results of a study of the process of transporting grain from the territory of Ukraine in global supply chains. In order to study the negative impact of the transport sector, a simulation model of the existing logistics system was developed, namely, using only road transport. The model was developed using Java SE technology based on the agent-based and discrete-event principles. As a result of a series of experiments based on the grain supply chain through the Mykolaiv commercial port, it was found that the actual CO_2 emission rates per unit of transport work are 12.8 kg per tonne and 32.9 kg per 1000 tonne-km.

1. Introduction

Sustainable transport is a key factor in sustainable development. Due to the significant role and, accordingly, the impact of transport on sustainable development goals, the achievement of the Agenda and the Paris Agreement on climate change is ensured or hindered. Unlike sectors such as energy and water supply, which rely on SDGs to track sector performance, transport does not have a specific SDG. Nevertheless, transport has important socio-economic importance, contributes to economic and social development and is the basis of public welfare.

Modern transport and logistics (TL) systems are in a state of constant change, adapting to the external environment, taking into account new challenges and implementing the achievements of scientific and technical progress, but from the standpoint of sustainable development, these changes are not enough to ensure a full transition to sustainable transport. At the same time, achievements and results in this area create unique opportunities for rethinking passenger and cargo transportation systems and finding sustainable solutions to accelerate transformation processes on a fundamentally new basis.

Sustainable transport means the provision of TL services and the use of infrastructure for the mobility of people and goods, promoting economic and social development for the benefit of present and future generations in a safe, accessible, efficient and resilient manner, minimizing carbon emissions and other emissions and environmental impact. The process of transition of TL systems requires the use of an integrated approach, which is based on the awareness of positive impacts and the avoidance or mitigation of negative consequences.

Meanwhile, analysts say that freight volumes will continue to grow. It is expected that road freight traffic will grow by about 40% by 2030 and 80% by 2050 [1]. This directs transport policy towards reducing road transport and using less polluting and more energy-efficient types of vehicles. While we fully agree with the need for this kind of transformation, we emphasise that technological factors, in particular the application of sound approaches to multimodal transport planning, can have a significant impact on the sustainable operation of transport lines. According to the EU transport policy, along with internalisation of external costs, more targeted investments in physical infrastructure, direct support for intermodal transport, and better use of information are key types of actions to support greater use of multimodal solutions [2], which require appropriate methodological support.

2. Problem description and method

Due to the fact that multimodal transportations are complex TL systems with a significant number of objects, technological processes and random variables, and, accordingly, certain events are difficult and sometimes impossible to predict, the simulation modelling methodology is used for their planning. Simulation modelling, thanks to its powerful mathematical apparatus, allows covering a significant number of TL parameters of the multimodal transport system, reflecting the dynamics of processes and taking into account uncertainty.

Simulation modelling (SM) methods are used in operations research to support decision-making. Modern SM research can include the development of models using a specific modelling technique (discrete event modelling, agent-based modelling) or hybrid modelling (interdisciplinary and combined) [3]. Discrete event simulation (DES) is the process of codifying the behavior of a complex system as an ordered sequence of defined events that occur at a certain point in time and indicate a change in the system state [4]. Agent-based modelling (ABM) explores the behavior of autonomous agents, the interaction between agents and the environment, as well as the impact of behavior on the most complex aspects and adaptation of the system as a whole [5–7]. Each of these approaches has a rather long history of development. Meanwhile, the hybrid modelling approach (HS), which is based on the use of interdisciplinary approaches at different stages of modelling or combines two or more methods, including discrete event modelling, system dynamics and agent-based modelling (combined modelling), has experienced an almost exponential increase in popularity over the past decades [8, 9].

Researchers offer a number of important contributions that present simulation modelling methods as tools for solving various issues related to the development of TL systems of multimodal transport. Approaches are being developed to classify this contribution in the context of identifying the most researched areas, established trends and promising areas of research [10]. At the same time, it is argued that despite the exponential growth of academic literature, there is a gap for empirical research on the numerous drivers, barriers, theories, moderators, intermediaries and methods related to supply chain sustainability [11]. It is even noted that due to the growing sustainability concerns, simulation models have become limited in minimizing, for example, CO_2 emissions during transportation planning, as they are not goal-oriented as optimization models [12].

The analysis of individual publications allowed us to summarize the following observations on the methodological features of a number of studies. Carlos Henrique et al. [13] presents an approach to modelling and optimizing planning to minimize carbon emissions in grain logistics export chains while meeting demand requirements. The results show the possibility of reducing emissions, but the data and therefore the conclusions are limited to railways. Matsiuk et al. [14] presents agent-based simulation models that allow for a comprehensive assessment of the performance of complex queuing systems. However, in these studies, the probability of technological failure is considered to be a complex indicator, rather than technological indicators, such as service time. In [15] delivery speed is considered from the perspective of the entire supply chain based on a simulation model and data that combines information from line operators and customers to analyze how they influence decision-making in maritime supply chains. Katsman et al. [16] considers a multifactor queuing system. Using an analytical model of the system states, the authors determine the performance indicators of a complex, multifactor queuing system. However, this approach has certain limitations for use in the study of complex supply chains. Studies have shown that the impact of speed can be small in terms of total supply chain costs, but quite significant in terms of carbon emissions. Mazaraki et al. [17] presents a simulation model of grain delivery by rail and water transport, and although the process is multiphase, it does not take into account the use of road transport as a means of transporting grain from production sites to railway stations.

Based on the hypothesis put forward and taking into account the results of generalization of the latest methodological tools, the purpose of this study is to determine the optimal parameters of the process of grain supply by road to Ukrainian seaports. To achieve this goal, it is planned to:

- to develop a network simulation model of grain delivery by a centralized fleet of vehicles from production sites to grain terminals of seaports;
- to study the conditions of sustainable functioning of the transport and technological line "production points – road transport system – sea trade port";
- based on the optimal technical and operational characteristics of the grain supply chain, to determine the specific CO_2 emissions per unit of transport work.

3. Results and discussion

The complete turnover of the vehicle in the grain supply chain structure will be equal to:

$$Q_{to} = t_{waitL.} + t_{l.} + t_{moveToSeaPort.} + t_{waitUnl.} + t_{Unl.} + t_{moveToBack.} \tag{1}$$

where $t_{waitL.}$ is the time spent waiting for the loading operation, hours; $t_{l.}$ is the time spent on loading grain, hours; $t_{moveToSeaPort.}$ is the time spent on moving the vehicle to the seaport terminal, hours; $t_{waitUnl.}$ is the time spent waiting for the unloading operation, hours; $t_{Unl.}$ is the time spent on unloading, hours; $t_{moveToBack.}$ is the time spent on moving the vehicle from the sea terminal to the point of the next loading, hours.

More generally, expression (1) can be represented as:

$$Q_{truck} = \sum t_{t.w.o.} + \sum t_{exec.} \tag{2}$$

where $\sum t_{t.w.o.}$ is the total waiting time for operations. This element can be interpreted as unproductive vehicle downtime, hours; $\sum t_{exec.}$ is the total executional time of operations. This element can be interpreted as the time of vehicle use, hours.

Then the vehicle utilization rate will be defined as:

$$\upsilon_{truck} = \frac{\sum t_{exec.}}{\sum t_{t.w.o.} + \sum t_{exec.}} \tag{3}$$

At the same time, grain delivery time significantly depends on the efficiency of the vehicle fleet and, for network processes, is a derivative of a set of transport and technological parameters. Taking into account that the delivery time should be as short as possible, subject to the rational use of production resources, we obtain the following optimization model:

$$t_{deliv} = f(k_{grain}, N_{truck}, N_{elev}, \{M_1 : M_k\}) + f(m_{truck}, N_{truck}, \{M_1 : M_k\}, N_{elevseaPort}) \to min. \tag{4}$$

with restrictions:

$$f(n) = \begin{cases} z_r < r_{truck} < z_f, \\ m_{truck} = 1, 2, 3...M_{truck}, \\ N_{truck}, N_{elev}, m_{truck}, N_{truck}, \{M_1 : M_k\}, N_{elev.seaport} > 0. \end{cases}$$

where k_{grain} is the average intensity of formation of grain cargo mass, tonnes/year; N_{truck} – estimated fleet of trucks, units; $N_{elev}, N_{elev.seaport}$ – the estimated required capacity of elevators at the primary point of grain accumulation and elevators at the seaport, tonnes; $\{M_1 : M_k\}$ – the multiplication of possible routes of grain delivery by road on the grain supply network; z_r is the rational limit of vehicle fleet utilization; z_f is the limit of reliability of the vehicle fleet.

Since the objective function of the optimization model is presented in implicit terms, its implementation will be carried out through computer simulation.

The simulation model is a computer model that simulates the process of transporting grain from the places of its production – the primary storage network – to the terminals of sea grain ports.

The model was developed using a hybrid approach based on two basic principles of simulation modelling: agent-based and discrete-event modelling [18]. The agent-based principle allows for the full application of system factor analysis, as the agent model is a multi-element system operating in a single development environment based on the main agent. The discrete-event principle allows you to simulate a technological process of any complexity in detail. In this case, this tool is used to simulate the full technological turnover of a vehicle – a truck.

The model was implemented on the example of the Mykolaiv Commercial Port and the region of attraction to it – Mykolaiv, Kirovohrad, Dnipro, Zaporizhzhia and Kherson regions in the GIS

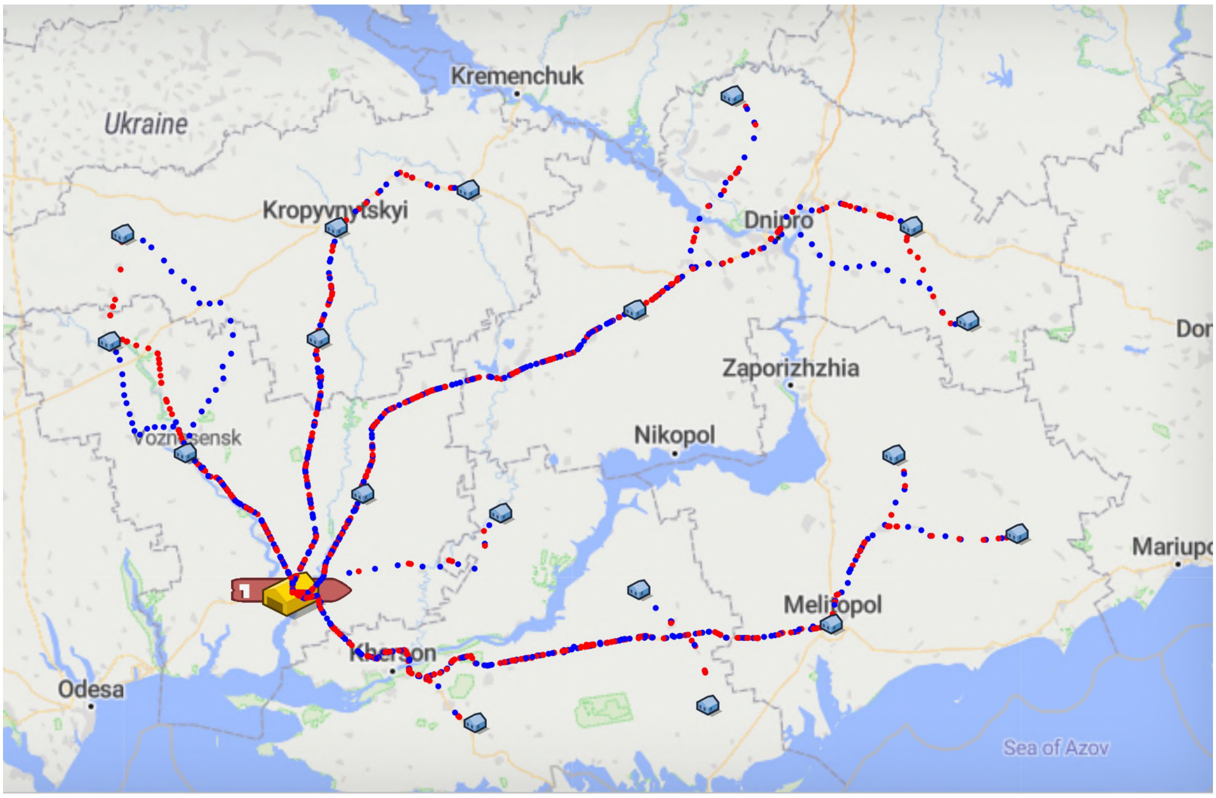

Figure 1. General view of the presentation of the simulation model.

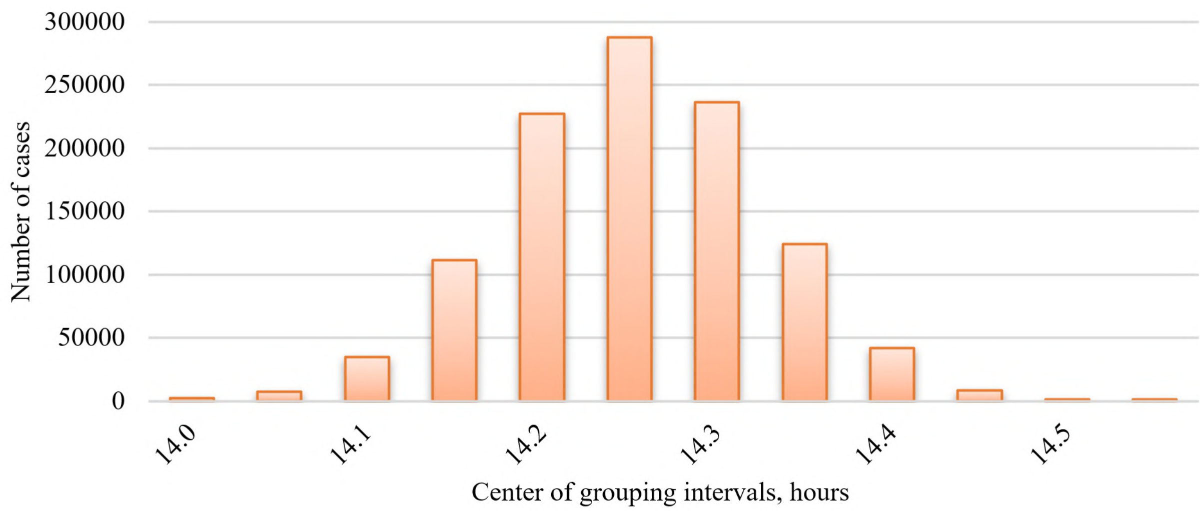

Figure 2. Probability density of grain delivery time distribution at optimal sizes of the fleet of vehicles (trucks and ships).

spatial environment of a real map of road routes using the Java SE technology and compiler. Initial data and grain production volumes were taken in accordance with official statistics for these regions for the 2021-2022 marketing year, totaling 14.5 million tonnes.

The general view of the model presentation is shown in figure 1.

According to the modelling results, the regularity of formation of the average level of vehicle fleet utilization (load factor) depending on the number of trucks involved in the transportation process has been established (figure 2). It has been experimentally established that the optimal level of vehicle fleet utilization of 51% is achieved at 2300 units. At a load factor of 47% of the bulk carrier fleet, the average time spent by a tonne of cargo in the transport system is 14.2 hours and has an almost perfect normal law distribution density with parameters $M(x) = 14.22$ hours and $s(x) = 0.113$ hours.

CO_2 emissions per unit of transport work (one ton-km) and one transported ton of cargo were determined (table 1).

Table 1. Experimental results.

Indicator	Indicator value
Average delivery time, hours	14.3
The average distance of the cargo route, km	391
We need a fleet of trucks (carrying capacity 20 tons)	2300
The coefficient of utilization of the car park	$p = 0.55$
Average costs of diesel. fuel for the delivery of 1 ton of cargo by land, l.	4.21
Average costs of diesel. of fuel per 1000 ton-km, l	5.34
CO_2 emissions for the transportation of a ton of cargo over land, kg	12.8
CO_2 emissions per 1000 ton-km, kg	32.9

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4. Conclusions

A network simulation model of grain delivery by a centralized fleet of cars from production sites to grain terminals of sea trade ports has been developed, which, unlike the existing ones, takes into account the time spent waiting for loading / unloading and simulates the full cycle of car turnover under centralized control. It has been established that the sustainable functioning of the transport and technological line of grain – the level of use of vehicle fleets within the range of 50–60% in the conditions of Ukraine – is achieved with the size of the fleet of trucks (with a carrying capacity of 20 tons) of 2,300 units for every 14.5 tons of grain. On the basis of the defined technical and operational indicators, the actual norms of CO_2 emissions per unit of transport work were established: 12.8 kg per ton and 32.9 kg per 1000 ton-km of grain transported over land.

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Strategic approach to sustainable development of railway transport and optimizing the use of empty cars in organizing transportation of dangerous goods

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Abstract. Under present-day conditions in the development of the transport market, organizing the transportation of dangerous goods by rail is an urgent task, considering the specific properties of the impact of dangerous goods on technical devices, human health, and the environment. The number of parameters influencing the safety of the transportation process is quite large, therefore, programs for the safe and sustainable development of railway transport must involve protection from all possible sources of danger. The strategy for sustainable development of railway transport should be based on improving regulatory and technical documentation, developing safe technology for eliminating the consequences of emergencies, developing network computer technologies, and improving vehicles and transportation technology. Since the transportation of dangerous goods represents a significant share of the total transportation of goods, including railway transport, the research outlined in the presented work is aimed at solving some aspects of this strategy, which as a result forms a strategic approach to the sustainable development of railway transport when organizing the transportation of dangerous goods. In this paper, considering modern conditions for the development of railway transport, it is proposed to comprehensively implement the assigned task with a new approach by introducing a system of operational control during the transportation and temporary storage of dangerous goods and applying the developed method for the optimal distribution of empty cars among cargo checkpoints in the organization of the transportation process.

1. Introduction

Transportation of dangerous goods is an activity associated with the movement of dangerous goods from the place of their production or storage to their destination, with the preparation of freight, containers, vehicles, and crew, acceptance of freight, freight operations, and short-term storage of goods at all stages of movement [1–3].

Transportation of dangerous goods, including railway transport, is a necessary task in the context of sustainable development of transport, since ensuring the sustainable organization of such transportation will maintain the health of personnel and the population, exclude negative impacts on the environment, and take all necessary actions to prevent the occurrence of an emergency [4–6]. On the one hand, this direction corresponds to Sustainable Development Goal No. 9 “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovations”, and on the other hand, it satisfies the provisions and Sustainable Development Goal No. 11 “Make cities inclusive, safe, resilient and sustainable”, No. 12 “Ensure sustainable consumption and production patterns”, No. 13 “Take urgent measures to combat climate change and its impacts” [7].

These provisions characterize the implementation of the environmental component in the concept of sustainable development. At the same time, the research presented in this work is also aimed at optimizing the organization in the transportation of dangerous goods by optimally allocating empty cars through freight points. This will ensure economic stability, which is confirmed by the results of the research. Thus, the relevance of the chosen research topic is due to the desire for a balanced development of the economic and environmental components in the concept of sustainable development through the implementation of the proposed strategic approach to organizing the transportation of dangerous goods by railway in Ukraine.

Since the transportation of dangerous goods by railway is a specific type of transportation, with regard to the potential danger of transporting goods, the unconditional implementation of all preventive measures aimed at warning the occurrence of emergencies when organizing the transportation of dangerous goods, including by railway, is required from all entities in the transportation process [8–10].

Confirmation of the relevance and need to formalize a strategic approach to sustainable railway development in organizing the transportation of dangerous goods is statistical data on the number of dangerous goods transported in 2018-2022, as well as the number of accidents, transport events and emergencies that occurred in Ukraine during the transportation of dangerous goods for the same period [11]. These data are presented in tabular and graphical forms (table 1, table 2, figure 1). The materials provide statistical data under the classification of dangerous goods (classification by class, category, and packaging group) in line with State Standards of Ukraine (SSU) 4500-3 “Dangerous goods. Classification” depending on the type and degree of their potential danger according to indicators and criteria [12].

Data from table 1 and figure 1 show that the highest rates of dangerous goods transportation in Ukraine were in 2019 and 2020. In 2022, we see a rapid decline in the volume of railway transport, also due to certain problems in logistics.

A significant proportion of chemically hazardous facilities are concentrated on the territory of Ukraine, as well as a significant number of fire-hazardous facilities, which are usually located next to railway tracks or have their private tracks. At the above potentially hazardous facilities, large quantities of hazardous substances are extracted, processed, transported, stored, and consumed, which in any case require further safe transportation [13–15].

Considering the above, in modern conditions, it is especially relevant to review the current technology for transporting dangerous goods, including in bulk, along the Ukrainian railway network, and to find ways to improve it to prevent the occurrence of emergencies, which increased in the period from 2018 to 2022 by 22 percent (table 2).

It should also be noted that complex European integration processes relating to Ukraine and its transport system [16–18], different levels of economic development, and the characteristics of the productive and consumer specialization in the EU countries and Ukraine will lead to the fact that the volume of transport of dangerous goods in Ukraine and beyond will steadily increase [19]. This requires the search for effective tools to optimize the organization of dangerous goods transportation by railway in Ukraine.

The work is devoted to formalizing a strategic approach to organizing the transportation of dangerous goods by introducing a system of operational control during transportation, temporary storage of dangerous goods, and formalizing the optimal allocation of empty cars

Table 1. Percentage ratio in the number of dangerous goods transported following the class of dangerous goods from 2018 to 2022.

Danger class	2018	2019	2020	2021	2022
Class 1 Explosive Materials	15.89	10.88	10.52	9.35	10.16
Class 2 Gases	23.20	16.08	15.35	16.23	17.71
Class 3 Highly flammable liquids	10.39	18.07	20.73	18.04	16.32
Class 4.1 Inflammable solid	4.81	4.88	6.64	7.21	10.17
Class 4.2 Substances capable of self-ignition	8.36	7.12	6.92	6.07	5.87
Class 4.3 Substances that emit flammable gases interacting with water	3.38	3.67	3.36	2.23	3.46
Class 5.1 Oxidizing substances	7.06	10.57	7.93	9.36	8.92
Class 5.2 Organic peroxides	12.72	6.56	7.02	8.01	10.49
Class 6.1 Toxic substances	3.86	1.72	5.36	4.02	1.72
Class 6.2 Infectious substances	0.00	$1 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	0.00	0.00
Class 7 Radioactive Materials	0.00	$1 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	0.00	$4 \cdot 10^{-6}$
Class 8 Corrosive Substances	4.51	6.22	9.67	10.84	3.50
Class 9 Other hazardous substances	5.80	14.23	6.50	8.65	11.66
In total	100.00	100.00	100.00	100.00	100.00

Table 2. Number of transport events with dangerous goods.

Number of	2018	2019	2020	2021	2022
Transport events	130	141	147	154	161
Lost	29	17	11	6	8
Injured	9	7	11	6	4

among freight points to ensure the implementation of the concept of sustainable development of railway transport in Ukraine.

2. The operational control system for the transportation and temporary storage of dangerous goods

An analysis of transport events related to the transportation of dangerous goods [11] shows that the so-called "human factor" remains decisive in the issue of ensuring safety [20–22]. In modern conditions, it can and should be assessed even at the stage of admission to work with dangerous goods by introducing a unified system of professional training, qualified selection, and certification of personnel whose activities are directly linked to dangerous goods.

In solving this problem, an important role is assigned to the audit apparatus, its professional selection, and advanced training.

Railway transport is equipped with automation facilities at a fairly high level. At the same time, research is aimed at reducing the number of technical equipment failures and personnel errors. The developed multi-level system for controlling and ensuring the safety of train traffic allows, in addition to performing direct control and safety tasks, to detect potentially dangerous situations. In this case, the dispatch apparatus (assistant station masters, train dispatchers) is given a corresponding signal, and the priority for processing information that comes from the control and monitoring object is set. The system also provides for the development of predicting

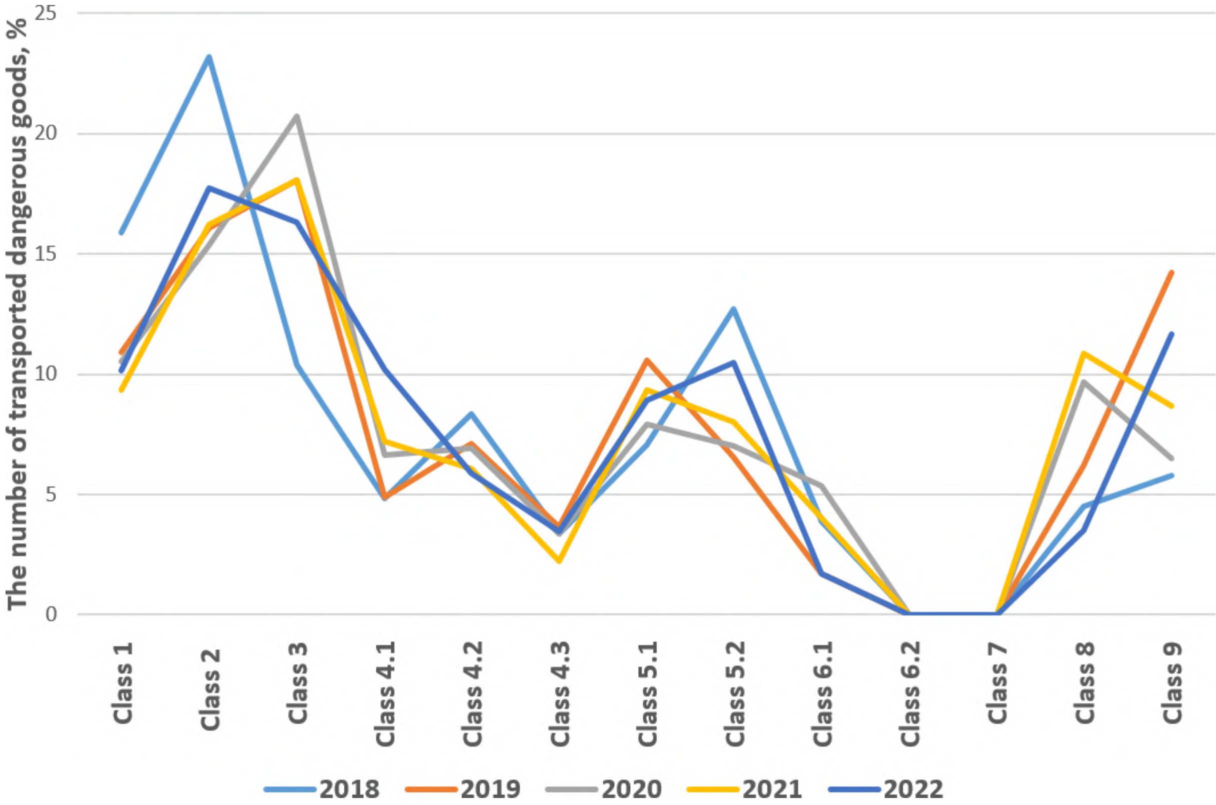

Figure 1. The number of transported dangerous goods in 2018-2022, in percentages.

the development of the situation in the event of accidents or emergencies and the development of model options for switching on backup control subsystems and ensuring the safety of train traffic.

In general, the implementation of the system involves reducing, and in some cases eliminating, the influence of the human factor on the safety of train traffic. To do this, erroneous actions of the dispatch apparatus and incorrect operation of devices in the event of a dangerous failure or unauthorized interference in their operation are blocked.

Environmental control points at border checkpoints play an important role when organizing the international transport of dangerous goods.

One of the main problems when transporting dangerous goods, including in bulk, is the insufficient level of reliability of rolling stock. An analysis of recent accidents associated with the transportation of bulk dangerous goods shows that in several cases rolling stock with an extended service life was used (for example, shippers have the majority of such specialized tanks). The tanks used do not have technical means to reduce the evaporation of petroleum products, casings to protect drain devices from impacts on the ground, and the boiler body is structurally unable to withstand an impact on the ground when there is a tank derailment. New generation tanks having a reinforced boiler body are practically not being introduced. The railway management is taking the initiative to renew the tank fleet. In light of this, it would make more sense to incentivize shippers of dangerous goods to upgrade their cars. In addition, it is necessary to tighten control when accepting bulk dangerous goods for transportation from the shipper, especially paying attention to the following points:

- control of the technical condition of tanks, including control of non-interference in their design without agreement with the manufacturer;

- monitoring compliance with the conditions for loading goods into cars following established rules and instructions for tanks;
- control of correct completion of transportation documents, availability of necessary permits and licenses;
- control of compliance with the rules of escort and security.

When organizing the transportation of dangerous goods in bulk, it is necessary to monitor compliance with the transportation conditions provided for by the rules. For this aim, using modern automation tools, it is proposed to develop and equip tanks with technical means that reduce the evaporation of petroleum products during transportation in tanks. In addition, it is possible to install sensors that monitor and signal the state of dangerous goods during transportation. Information about deviations in the state of the control object is immediately transmitted to the provided levels of automated systems and the staff makes a prompt decision on further actions.

As a rule, the onset of a destructive process with dangerous freight (seepage, leakage, evaporation, etc.) begins with a slight depressurization of the container and can subsequently result in a significant negative impact on the environment, both during transportation and temporary storage of dangerous goods at the transfer station.

Moreover, if depressurization occurs along the way, then the dangerous freight can leave a trail of tens or even hundreds of kilometers long during the time from the beginning of the depressurization process until the moment it is detected. Therefore, it is very important to define the beginning of an emergency as soon as possible and begin to neutralize its consequences.

Creating a system to prevent transport incidents when transporting dangerous goods will undoubtedly reduce environmental and economic damage.

The operational control system for the transportation and temporary storage of dangerous goods includes a set of technical systems, devices, and measures to monitor the condition and location of dangerous goods, determine the onset of emergency (pre-emergency) situations and accidents, process information and transfer it to dispatch control centers for developing solutions to prevent emergencies, localize and neutralize the consequences of accidents.

The system for operational monitoring of the condition of transported and stored dangerous goods includes the following technical subsystems and devices:

(i) subsystems for monitoring the technical condition of containers for the transportation of dangerous goods and the condition of them themselves to determine their release into the environment using sensors;
(ii) subsystems for collecting information from control sensors, processing it, and transmitting it to a repeater installed on the locomotive;
(iii) subsystems for transmitting information from the locomotive (train, car, warehouse) to train dispatchers and processing it.

To determine the economic efficiency of implementing an operational control system during the transportation and temporary storage of dangerous goods, research is needed to define the resulting economic damage that causes costs for:

(i) liquidation of the accident and its consequences and restoration of traffic;
(ii) compensation for damage to the environment (including to the population) – fines and compensation;
(iii) losses from the cessation of the transportation process during the liquidation of the accident (including damage to vehicles);
(iv) possible payments for freight insurance.

Determining such average costs will allow us to evaluate the effectiveness of implementing the system, and organizational and technical solutions for eliminating accidents and their consequences.

Sensors control for monitoring the condition of dangerous goods can be made in the form of sensors that can not only signal the occurrence of leaks of substances, but also indicate their locations (by using an additional substance that can change the colour), and also allow them to be quantitatively assessed. Monitoring sensors together with the unit of a primary information collection must meet the technical requirements. In addition, they must have protection systems against dynamic loads, vibration, external damage, exposure to aggressive substances, and unauthorized penetration.

The placement and fastening of sensors and the primary information unit on special tanks must be permanent and have connectors for connecting the information transmission system.

The issue of reducing the threat of an emergency with dangerous goods transported in bulk through the territory of Ukraine plays an important role since accidents accompanied by spills of hazardous liquids lead to significant environmental damage to the environment.

In this regard, it is rational to develop and implement technology to eliminate the consequences of transport accidents with dangerous goods. In addition, it is possible to develop a methodology and determine environmentally acceptable routes for dangerous goods to reduce the risk of an emergency.

Considering that more than 90 percent of liquid freight consists of petroleum products, great attention must be paid to improving the organization of their transportation. The achievements of scientists make it possible to optimize the car flows of petroleum products. In this case, important conditions are the routing of their transportation and the organization of empty tank car flows.

Routing of railcar flows of petroleum products is a particularly effective measure for mass export transportation to seaports, which allows for reducing freight delivery times and speeding up the turnover of railcars.

Also, one of the sources of reducing costs and car turnover is the rational allocation of empty tanks for loading. At the same time, it is taken into account that in the case of loading a freight similar to the dumped one into a tank, there is no need for hot working of the tanks (cold working is sufficient), and this can significantly reduce the downtime of tanks at loading stations and the costs associated with processing.

The rational allocation of empty tanks for loading consists in increasing the degree of conformity of the structure of tanks arriving for loading, according to the names of the dumped and filled petroleum products. This is possible by increasing the depth of information that is transmitted to loading stations about the names of dumped petroleum products from tanks arriving at their address in empty tank trains, and about the use of this information when distributing empty tanks for loading. The depth of information means the availability of the necessary information not about one composition of empty tanks for filling, but about 2...3 or more. Thus, with an increase in information to three trains, the proportion of tanks sent for loading of petroleum products similar to the dumped one increases by 2.5...3 times compared to the availability of information about only one train. Accordingly, a reduction in costs for washing and steaming operations is achieved and the turnover of tanks is accelerated.

The depth of required information can be increased by using modern information technologies. It is necessary that the dispatch apparatus make a timely decision on the assignment of trains of empty tanks to one or another loading station and that the necessary information is transmitted to them in advance to enable the rational allocation of tanks for loading.

Thus, the allocation of empty cars is a key and rather complex management task. The authors propose an optimal solution to the problem of distributing empty cars on freight points as one of the methods for optimizing the organization of transportation of dangerous goods by railways.

3. The description of the mathematical apparatus

Problems of the type under consideration can be divided into two groups depending on how fully all the factors associated with finding the optimal option for allocating empty cars are considered:

(i) optimization is done only from the viewpoint of the best use of the capacity of cars, and the costs associated with the movement of empty cars between freight points are not taken into consideration;

(ii) optimization of the process in the allocation of empty cars is carried out according to the criterion of overall operating costs associated with the supply of cars to freight points and with the transportation of goods by railways.

Ignoring the costs of supplying empty cars can be justified only if they do not differ significantly from each other or are insignificant in their absolute value.

In its simplest form, the problem of allocating different-type cars to freight points depending on the static load was formulated by A. B. Kaplan. In mathematical formulation, this problem is written as follows:

$$R^* = y_{ij}^{min} \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij}, \tag{1}$$

if

$$y_{ij} \geq 0, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m, \tag{2}$$

$$\begin{cases} \sum\limits_{i=1}^{n} y_{ij} P_{ij} = Q_j; \\ \sum\limits_{j=1}^{m} y_{ij} \leq n_i. \end{cases} \tag{3}$$

The main goal of drawing up an optimal allocation plan is to minimize the number of empty cars y_{ij}, required to transport a given amount of freight Q_j, if restrictions are imposed on the number of cars (3). In this case, at each freight point, there is only one type of freight j, the statistical load of which P_{ij} when transported in cars of the i-th type is given, and the costs of supplying empty cars are neglected. The sources of empty cars arriving at the freight points at the station are both unloading points and cars arriving from neighbouring stations.

The task of the type under consideration should be formulated differently if there is a shortage of empty cars:

$$R^* = y_{ij}^{max} \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij} P_{ij}, \tag{4}$$

if

$$y_{ij} \geq 0, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m, \tag{5}$$

$$\sum_{j=1}^{m} y_{ij} = n_i; \tag{6}$$

$$\sum_{i=1}^{n} y_{ij} P_{ij} \leq Q_j. \tag{7}$$

In this formulation, the optimization problem lies in finding such y_{ij}, that would maximize the linear form (4), representing the amount of freight loaded into n_i of delivered cars. At first

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sight, the optimal choice for distributing empty cars that mostly satisfies the requirements for the best use of capacity and tonnage is one in which only cars of one type are delivered to freight points.

However, with a significant number of freight points and a lack of empty cars of the "optimal" type, constructing such a distribution plan using heuristic methods seems impossible, and then the problem posed can only be solved using linear programming methods since functionals (1) and (4) and restrictions (3), (6) and (7) are linear.

4. Results

Let us consider a numerical example for conditions when there is a shortage of empty cars at the station. At two freight points there are freights in the amount of $Q_1 = 540$ tons and $Q_2 = 620$ tons, the volumetric weight of the freight is $y_1 = 0.3$ tons/m^3 and $y_2 = 0.75$ tons/m^3.

The station has three types of covered cars with the following characteristics for cars of the first type $P_1 = 62$ tons, $V_1 = 107$ m^3 in the amount of $n_1 = 8$, for cars of the second type $P_2 = 62$ tons, $V_2 = 120$ m^3 in the amount of 12 and for the third type of cars $P_3 = 62$ tons, $V_3 = 90$ m^3 in the amount of 6. The static loads of the cars are as follows: $P_{11} = 32$ tons, $P_{12} = 62$ tons, $P_{21} = 36$ tons, $P_{22} = 62$ tons, $P_{31} = 27$ tons, $P_{32} = 62$ tons.

The condition is set – to ensure the loading of all freights with a volumetric weight of $y_1 = 0.3$ tons/m^3. We will substitute the initial data of the task into expressions (4) — (7) and after transformations we obtain

$$R = 32y_{11} + 62y_{12} + 36y_{21} + 62y_{22} + 27y_{31} + 62y_{32} \tag{8}$$

or

$$R_1 = 1.2y_{11} + 2.3y_{12} + 1.3y_{21} + 2.3y_{22} + y_{31} + 2.3y_{32}, \tag{9}$$

$$y_{ij} \geq 0 \ (i = 1, 2, 3; j = 1, 2), \tag{10}$$

$$\begin{cases} y_{11} + y_{12} = 8; \\ y_{21} + y_{22} = 12; \\ y_{31} + y_{32} = 6. \end{cases} \tag{11}$$

$$\begin{cases} 32y_{11} + 36y_{21} + 27y_{31} = 540; \\ 1.2y_{11} + 1.3y_{21} + y_{31} = 20; \\ 62y_{12} + 62y_{22} + 62y_{32} \leq 620. \end{cases} \tag{12}$$

$$y_{12} + y_{22} + y_{32} \leq 10. \tag{13}$$

Let us exclude from expressions (9), (11) and (13) variables y_{12}, y_{22}, y_{31}, y_{32} and after simplification we obtain

$$R_2 = 0.46y_{11} + 0.7y_{21}; \tag{14}$$

$$y_{11,21} \geq 0; \tag{15}$$

$$0.2y_{11} + 0.3y_{21} \leq 4. \tag{16}$$

Condition $1.2y_{11} = 1.3y_{21} \leq 20$ is less strong than (16).

From conditions (11) it implies

$$\begin{cases} y_{11} \leq 8; \\ y_{21} = 12. \end{cases} \tag{17}$$

The task is to find such y_{11} and y_{21}, that would maximize the linear form (14). Since the task has been reduced to determining two variables, it can be solved graphically (figure 2). The search direction is shown by an arrow going from the origin of coordinates, since according to the condition it is necessary to maximize the functional (16), which grows with increasing

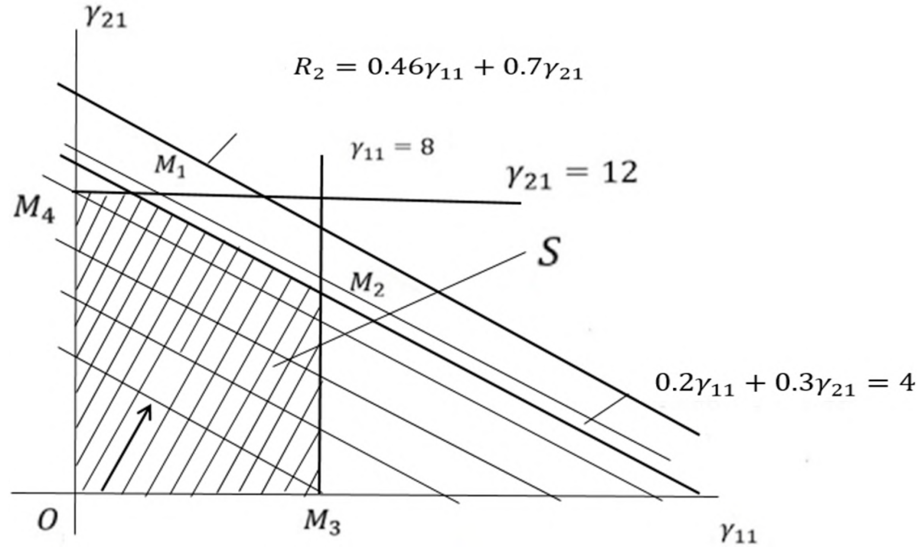

Figure 2. Graphical method for searching for the optimal option in allocating empty cars according to the criterion of maximum static load.

y_{11} and y_{12}. The desired solution should be sought in the area S, bounded by polygon $M_1M_2M_3OM_4$. Apparently, the coordinates of points M_1 and M_2 (that are farthest from the origin of coordinates) will correspond to the optimal solution.

Solving equations $0.2y_{11} + 0.3y_{21} = 4$ and $y_{11} = 8$, together, we determine the coordinates of point $M_2 : y_{11} = 8, y_{21} = 8$. As a result of the joint solution of the equations $0.2y_{11} + 0.3y_{31} = 4$ and $y_{21} = 12$ we obtain the coordinates of point $M_1 : y_{21} = 12, y_{11} = 2$. To establish the optimal solution, we substitute the coordinates of the points M_1 and M_2 into expression (14) and as result we have $R_2(M_2) = 9.28, R_2(M_1) = 9.32$. Thus, the coordinates of point $M_1 : y^*_{21} = 12$ and $y^*_{11} = 2$ are the optimal solution. Using equitation (11) and (12), we calculate the remaining components of the optimal solution: $y^*_{12} = 6,\ y^*_{22} = 0,\ y^*_{31} = 2,\ y^*_{32} = 4$. For this solution, the value of the functional will be equal to $R = 1100 tons$ and the balance of unshipped freight will be $(540 + 620) - 1100 = 60$ (tons).

The proposed method for finding the optimal option in distributing empty cars according to the criterion of maximum static load is a distinctive option for solving the problem of distributing empty cars in railway transport in comparison with currently existing methods. For example, in [23], the optimization model for the problem of distributing empty freight cars at a railway site is characterized as a combination of the flow task with minimum cost with the task of selecting a vehicle route. In paper [24], the problem of distribution of empty cars in the Chinese railway system takes into consideration the requirements of timeliness of demand for empty cars. Based on this a spatiotemporal network is created to describe the process of distributing the empty cars, where, in terms of the types of cars and network capacity, an integer programming model is proposed, allowing to minimize the total costs in the distribution process. In line with the obtained results, the authors of [24] concluded that many train routes must be scheduled to guarantee the timely delivery of empty cars to the station. Thus, the proposed method for finding the optimal option for distributing empty cars according to the criterion of the maximum static load is a relevant tool for supporting operational decision-making on the rational distribution of empty cars, which is recommended to be used to optimize the transportation process in railway transport in general, and when organizing the transportation of dangerous goods particularly.

5. Conclusions

Thus, due to the increasing attention of the world community to the global problems of humanity and the strategy for creating equitable and dynamic economic growth, sustainable transport is becoming one of the most important areas of further development. Sustainable transport has a positive impact on the environmental, social and economic stability of society.

Based on the research, we can conclude that the realization of the proposed strategic approach in optimizing the transportation of dangerous goods, which is determined by the implementation of an operational control system for the transportation and temporary storage of dangerous goods and the realization of the optimum allocation of empty cars among freight points, will ensure:

- improving transportation technology, increasing the level of their implementation, and ensuring the prevention of emergencies with dangerous goods during transportation on the Ukrainian railway network;
- realization of the “National Transport Strategy of Ukraine for the period of up to 2030” by solving the problem of increasing the level of safety in transport by introducing a system of operational control during the transportation and temporary storage of dangerous goods in order to ensure a high level of safety during the transportation of dangerous goods;
- compliance with the principles;
- realizing the concept of sustainable development, since the goal of the research corresponds to the three goals of sustainable development in concordance with the official document of the UN General Assembly “Transforming Our World: The 2030 Agenda for Sustainable Development” (goals 9, 11-13 [7]).

It is also worth noting that the need for the modern development of railway transport and technological systems in a single transport space, the development and implementation of effective transportation process management systems require the creation of new and adjustment of existing methods for the distribution of freight and car flows [23, 24]. Therefore, with a view to optimizing the transportation process in railway transport in general, and when organizing the transportation of dangerous goods in particular, the use of the proposed method for finding the optimal option for distributing empty cars according to the criterion of maximum static load is a relevant tool for supporting operational decision-making, which will provide a solution to the important operational task of rational distribution of empty cars among cargo points.

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A flight situation advisory system for uninterrupted and efficient air transportation

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A flight situation advisory system for uninterrupted and efficient air transportation

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Abstract. Safe and reliable air transportation plays a significant role in modern society by facilitating connection, communication, and economic activity, which has been growing steadily for recent decades. Ensuring a safe, reliable, and efficient operation of the air transportation network is a central challenge in assuring smooth progress in modern and future aviation. This research addresses the problem of human-caused issues in aerial transportation by proposing, substantiating, validating, and designing automated flight situation advisory systems that can provide critical input to the crew in the cases of unexpected and challenging flight situations. It was shown that a proper design and use of these systems could be instrumental in managing flight situations and could eliminate or mitigate a significant fraction of human-cause faults and emergencies. It would expected that such an advisory system can become a proactive and cost-effective tool to improve safety and reliability in the operation of air traffic networks of today and tomorrow. The study's main result is to assess the importance of factors influencing the development of recommendations by the advisory system.

1. Introduction

Air transportation plays an important role in the life of modern society. This conclusion is confirmed by the data of the International Air Transport Association [1], which established that over the past two years, there has been an increase in air transportation of passengers and cargo in the world, which is associated with the lifting of restrictions imposed during the onset of the COVID-19 pandemic.

In addition, air transport is an effective means of facilitating the solutions to social and international challenges such as humanitarian and military aid delivery, evacuation of victims of natural disasters, diplomatic visits, development of commercial and social projects, and others.

As the role and critical nature of air transportation has been increasing steadily, more attention is being paid to improving the quality of the aircraft and their safe, reliable and efficient use. Current trends in air transport development are aimed at reducing air emissions and noise level of aircraft engines, developing optimal strategies in route formation to reduce the cost of transportation, studying different flight and approach/landing scenarios, improving the quality of pilot training, studying technological and behavioral strategies aimed at solving the needs of both the carriers and the passengers.

Improving the safety and efficiency of air transport utilization is also influenced by the study of air catastrophes, not the least, examination, investigation, determination and the elimination of their causes. Many aircraft faults and failures leading to serious accidents are not so much of technical origin but rather can be related to incorrect decisions and actions, improper crew activities and other human-caused issues. Thus, according to ICAO estimates, the human factor can account for about 80% of all air accidents [2].

Thus, ensuring the correctness of the crew's actions in difficult flight conditions can be an essential challenge in the pursuit of safe and efficient air transportation. One of the possible solutions for an accident-free operation of air transport can be the creation of Automated Onboard Assistants (AOA), such as advisory expert systems that could assist in both finding and executing the solutions to complex flight situations based on the characteristics, the prognosis of the flight situation and provide the crew effective with effective solutions for specific developing flight situations [3]. The basis for analyzing the current state of the aircraft can be based not only on the information from the diagnostic systems of the craft but also integral indicators of the route progression, which ensures a smooth and reliable flight.

The purpose of the research is to design and create effective onboard advisory expert systems that analyze real factors that determine flight safety, which will ensure the rapid implementation of such systems on an aircraft in the interests of developing sustainable and acceptable air transport.

2. Related work

The main idea of air transport advisory systems is based on the construction of reliable and productive onboard computer systems developed in the interests of space, air, and ground vehicles.

Würfel et al. [3] proposed the nearest approach to the definition of an onboard expert system for applications in manned aviation. The described system is represented by a two-level hierarchical knowledge base, the first level of which activates the problem adequate to the actual situation, whereas the second level solves the tasks of forecasting the development of the situation using the mechanisms such as a range of alternative solutions, product rules, and precedent decisions based on optimization problem.

A multi-factor hierarchical model for assessing the level of air transport safety based on an accurate assessment of the current state was developed by Bugayko et al. [4]. The model consist of 7 components and 29 indicators and evaluates economic, technological, social, and environmental that can influence a developing flight situation.

Studies of the properties of different types of motors to reduce environmental pollution were attempted in [5,6]. To this end, Eberle and Helmolt [5] studied variants of construction of electric energy storage sources of automobile engines based on accumulator batteries and hydrogen with the use of fuel cells for energy conversion. Jiménez-Crisóstomo, Rubio-Andrada and Celemín-Pedroche [6] studied the difficulties of transition to non-carbon energy paradigms in aviation technology.

New variants and principles of construction of onboard computers and their software were studied in [7, 8]. Fayyaz and Vladimirova [7] proposed the design of a satellite fault-tolerant distributed onboard computer (FTD-OBC), in which an adaptive middle-ware block was used to automatically migrate executing tasks from a faulty node to other nodes in a case of failure. Lüdtke et al. [9] presented a concept of an onboard computer for next-generation systems that address future requirements. This concept assumes a distributed reconfigurable onboard computer structure that utilizes off-the-shelf commercially available high-performance hardware components.

Lund et al. [10] studied a related approach involving the use of off-the-shelf performance software components in onboard computers. They considered middle-ware components that implement additional functions for modern space application computer hardware. Software updates for satellite systems onboard computers combined with cold, hot and Kim et al. [11] proposed warm redundancy, based on stochastic networks. Leppinen et al. described the development experience, design, initial flight test results, and lessons learned of the Linux-based Aalto-1 spacecraft flight computer [12].

Kato et al. [13] proposed an open source software project profile of Autoware that provides a set of control modules including localization, detection, prediction, scheduling, and control, enabling autonomous embedded vehicle computer systems. The study focuses on the performance of Autoware on ARM-based embedded computing cores and Tegra-based embedded graphics processing units (GPUs).

Kemmerer and Labelle [8] studied an onboard computer that collects standardized data for efficient disaster outbreak management, and improved competitiveness was presented. Brewer et al. [14] compared performance models obtained using data processing techniques to evaluate their equivalence. Problems and challenges in reliable and uninterrupted operation of networks of aerial vehicles based on protocols of distributed situation-aware intelligent decision systems were discussed in Shmelova et al. [15].

Gudmundsson et al. [16] formulated a concept of sustainable development in the context of transportation planning, management, and decision-making. The first part of the concept involves the development of indicators and a framework for measuring sustainable development in the transportation sector. In the second part, the authors analyze the actual planning and decision-making in transport agencies under different management conditions.

The impact of transportation in the context of human values is based on the put-forward quality of life indicators studied by Steg and Gifford [17] considered the evaluation of possible consequences of such a policy. They established a tendency to favor the use of transportation facilities by obtaining short-term benefits at the expense of long-term losses of society. Daley [18] formulated the criteria for the efficient use of air transportation contributing to sustainable societal development.

The analysis of the earlier studies shows that there is a need to develop effective onboard recommendation systems that ensure smooth and sustainable long-term operation of air transport in complex, uncertain, conflict, and other challenging situations in the operation of an aircraft.

3. Characteristics and criteria in uninterrupted operation

Even though air transportation safety has been improving, the absolute number of conflict situations has been increasing as well. The recognition that air flight professionals operate in complex rapidly evolving environments, additionally influenced by individual human factors came in the early 1990s [2]. Understanding the complexity of aircraft control leads to the need to increase trust in the automated means of detection and analysis of the situation and to use its recommendations to ensure the safety and uninterrupted character of the air transport mission.

Continuity of operation is defined by a set of indicators that affect the airplane's performance as a whole. These are reliability, safety, timing, and accuracy indicators of air transport operations [19].

The loss of air transportation service L, including those due to aircraft equipment failures in flight, can serve as an indicator of air transport usability by an organization. An element of this indicator can be aircraft reliability, which is characterized by the probability of failure-free operation of the aircraft within a specified time interval or by the operating time per failure.

Air transport safety S is a complex indicator that can be defined as the integral safety performance of various flight support services. For example, one of the indicators of air transport safety is the number of passengers injured in accidents. The output data can be information about the operating organization, which is usually represented by diagrams or graphs.

Uninterruptible is characterized by the disruption of the air transport schedule, delays T in cargo delivery, and passenger's arrival at the final destination. Possible causes of interruptions in the service can be external factors, such as weather conditions, efficiency of airfield support services, quality of pre-flight maintenance, technical condition of the aircraft, etc.

Technical errors E of the control system operation, which can be caused by external factors or failures of its elements; can account for up to 30 % of all service interruptions.

Next, one can introduce the integral indicator of uninterrupted operation of air transport that can be presented in the form:

$$I = \alpha L + \beta S + \gamma T + \delta E, \tag{1}$$

where α, β, γ, and δ is the scale (weight) coefficients satisfying $\alpha+\beta+\gamma+\delta = 1$, $\alpha > \beta > \gamma > \delta$.

The introduced indicator is of a multi-plane type, as it indicates that a trouble-free operation of air transport depends not only on the technical condition of the aircraft but also on the effective interaction of various services at all stages and in all phases of flight preparation and execution. Nevertheless, they can be assessed by the onboard recommendation system, which will strive to minimize the integral indicator of uninterruptible (1) during an active flight mission.

4. The structure of an onboard automated advisory system

The main requirements for the onboard-automated advisory system are based on the analysis of the current flight situation whereby the decisions are made on the accumulated knowledge in the order defined by the relevant recommendations and instructions [20]. The expert knowledge contained in the system is distributed across the following domains:

- recommendations of the actions in the current flight situation are made based on a detailed analysis of the external environment and the internal state of the craft;
- the crews can request a recommendation from the advisory system at any moment of the flight, whereas the situations of uncertainty, conflict and/or emergency have the highest priority compared to the others and can be initiated by the system automatically upon detection, without an explicit request from the crew;
- the order of actions in an advisory on actual flight situations is based on the rules formed based on previously accumulated experience taking into account the activities of the crew, the final decision is made by the flight professional with the sufficient level of expertise, experience, and authority;
- can accumulate, process, and incorporate new knowledge about actions in both already-known and novel situations.

The structure of the proposed system is shown in figure 1.

To realize these requirements, the onboard advisory system must receive information about the external environment and the current state of the craft from its own and external measuring devices such as sensors, indicators, and similar. These data are collected, analyzed, combined by categories, classified by priority, and based on the available rules and the knowledge incorporated in the system, a recommendation for the course of action is produced to the crew for execution. Thus, the onboard recommendation system should include the following subsystems:

- sensory, including its sensors and means of obtaining information from the outside world;
- data collection and analysis;
- categorization and prioritization;
- rules and knowledge base;
- decision-making and preparation of human-friendly recommendations to the crew, including specific control commands.

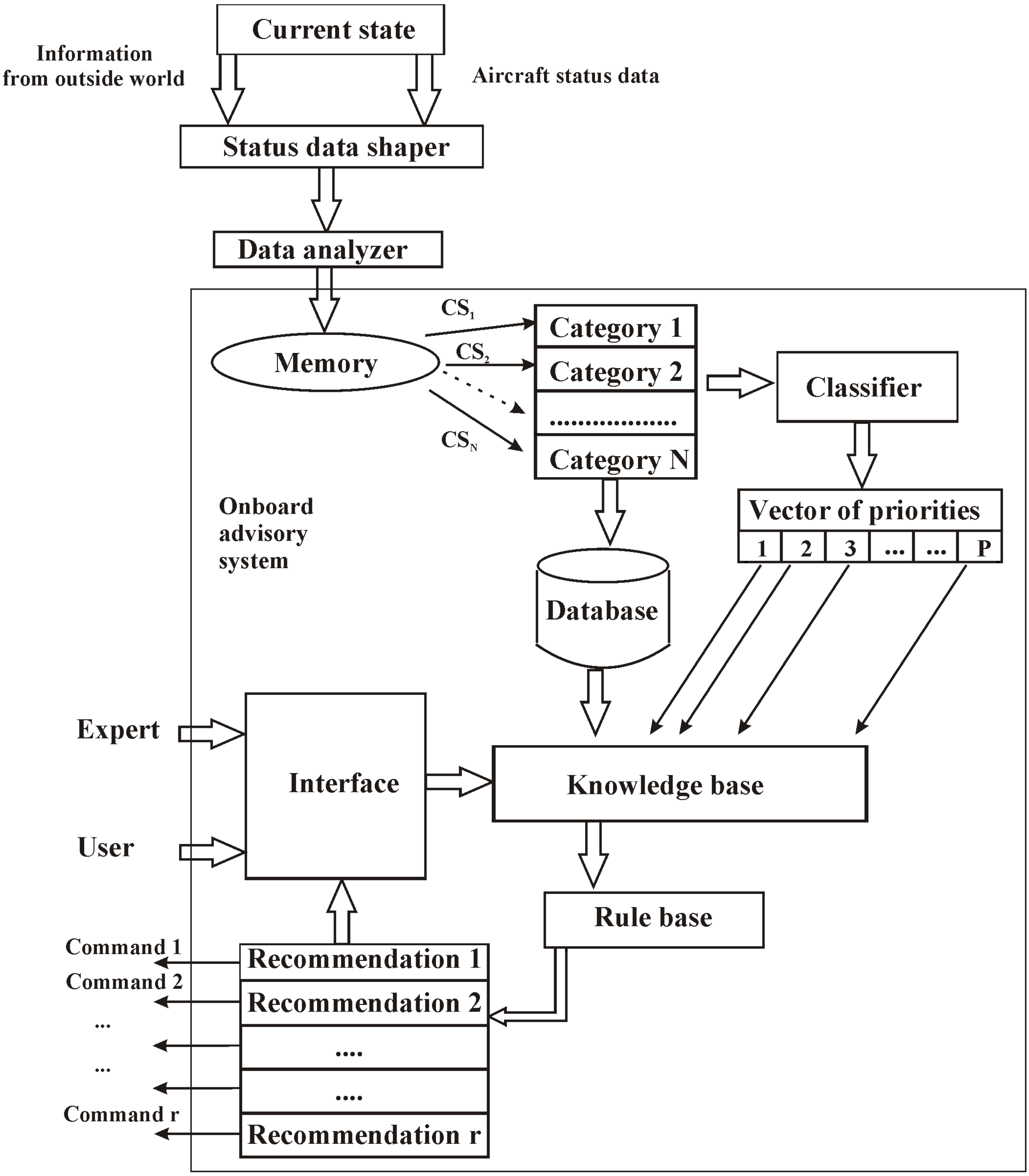

Figure 1. A general structure of an on-board flight advisory system.

5. Formalization of a functional aerial mission

The operation session consists of detailed organization and planning of the flight route. Planning a flight route requires careful study and correct selection of the parameter vector $X = (x_1, x_2, ..., x_n)^T$. Typical flight parameters are:

- *Departure and destination airports*
  In this stage, the flight planner selects a route that is specifically designed for each runway

and specific airport. In this case, it should take into account the aircraft's tracking from take-off to the start of the climb and between the last fixed point and the initial approach point.

- *Approximate takeoff weight*
  Based on the statistical information on the payload on the route, the takeoff weight is used to either be measured directly or estimated for the calculation of fuel consumption. If the flight plan is for a new route, using the maximum operational takeoff weight can be a good guess in this respect.
- *Air temperature range*
  Changes in air temperature in flight have a significant effect on engine fuel consumption.
- *Flight route*
  The route from origin to destination can be carefully selected using Jeppesen en-route charts, Skyvector [19, 20], or another application, taking into account, for example, the presence of a suitable airport on the route for landing in the event of an emergency, the presence of a noticeable obstacle in case of engine failure, etc.

When executing a route, typical flight situations are possible, comprising the vector $d = (d_1, d_2, \ldots, d_p)^T$. For example, in the case of a normal flight, deviation from the route, failure of one of the important flight support systems, etc.

The onboard advisory system calculates the numerical value of the priority of a typical situation, based on data received from various types of sensors. Based on the results of determining the priority of the situation, recommendations and actions of the crew, as well as commands to the autopilot, are formed that correspond to the specific situation. The priority values are normalized and are in the interval $P \in [0, 1]$, where the situation with the highest priority has a value of one, and the situation with a priority equal to 0 does not affect the execution of the flight mission.

A qualitative scale and a corresponding quantitative scale of priorities are introduced, for example, such as is presented in table 1.

Table 1. Priority scale.

Number	1	2	3	4	5	6
Priority, P	higher	high	middle	noticeable	low	not noticeable
P, value	1-0.9	0.7-0.8	0.5-0.6	0.3-0.4	0.1-0.2	less 0.1

The priority of a typical situation is calculated using the formula

$$P = \sum_{i=1}^{n} \alpha_i x_i, \tag{2}$$

In formula (2) x_i is data from sensors, it is assumed that these data are in the intervals

$$\underline{x_i} \leq x_i \leq \overline{x_i}, \tag{3}$$

where $\underline{x_i}$ and $\overline{x_i}$ are the lower and upper limits of sensor data measurement, and α_i are the coefficients that satisfy the data in table 1 and to be determined, taking into account the limitation imposed on them

$$\sum_{i=1}^{n} \alpha_i = 1, \tag{4}$$

where n is the number of sensors.

By using formula (2), sensor data is preliminary normalized following the expression

$$x_i^* = \frac{\overline{x_i} - x_i}{\overline{x_i} - \underline{x_i}}, \tag{5}$$

where x_i is the current value of the ith sensor, x_i^* is the current normalized value of the ith sensor. In the case of negative values of the parameters in (5), the absolute values of the measured quantities should be taken.

When sensor data makes an opposing contribution to (2), they should be divided into two groups to ensure an equal contribution between the measurement data. In this case, (2) should be applied in the form [21, 22].

6. Illustrative example

For the onboard system under consideration, a limited set of generalized factors are introduced that characterize the external situation, technical condition, pilot condition, and route change. It is assumed that their values change in relative units and are within the limits $x_i \in [0, 1]$. In this case, the worst values of the state indicators of the pilot and the aircraft are assessed by the highest values, i.e. take the value 0, and the best ones are rated 1, and the indicators of the external situation and route changes are vice versa, i.e. the worst value is 1, and the best corresponds to 0, the presence or absence of change.

Factor designations: x_1 are the values of the external situation indicator, EF, x_2 are the values of the technical condition indicator, TC, x_3 are the values of the pilot's condition indicator, FC, x_4 are the values of the route change indicator, RR.

The coefficients α_i from (2) are found by analytic hierarchy process, while two preference matrices are introduced for positive and negative views on priorities, in each of which the highest ratings are given to the technical condition and condition of the pilot about the factors of changing the route and the external situation, which allows us to obtain weighting coefficients:

$$\alpha_1 = 0.063, \alpha_2 = 0.384, \alpha_3 = 0.45, \alpha_4 = 0.102, \tag{6}$$

The obtained coefficient values correspond to the priority values given in table 1. The calculations carried out confirm the assumptions made.

A comparative diagram obtained based on calculations using formula (2) with weighting coefficients (6) is presented in figure 2, where the calculation was carried out for changes in each factor $xi \in [0, 1]$ and the values of other factors $x_j \neq x_i, x_j = 1$, allows us to establish the importance of priorities.

Figure 2 confirms the priority of the human factor and the technical condition factor compared to other factors when making decisions in an onboard recommendation system, all other things being equal.

7. The directions for implementation of onboard advisory systems

Design and implementation of onboard flight situation advisory systems comprises these areas and components:

- *Collection and processing of case data*
  Collection, and verification of flight situation data, and its processing into a compressed informative format that can be used in the rule/decision engine.
- *Design, implementation, and verification of the rule/decision logic and engine*
  Expert rules are formalized, defined, implemented, and verified with sample flight-situation data.

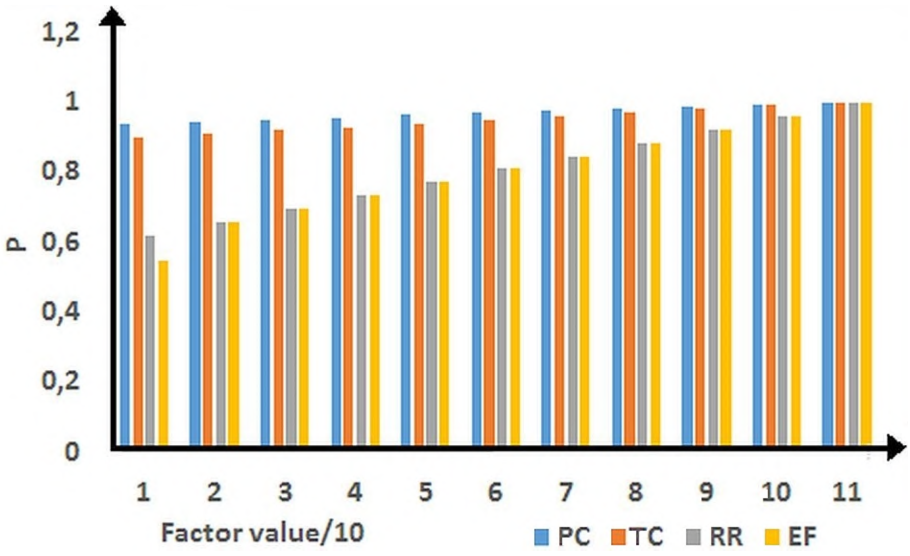

Figure 2. Comparative chart of relative importance of priorities.

- *Comprehensive verification of the rule/decision engine with validation of both actual and simulated data. Correction of faults and errors*
- *Optimization of the system's operational characteristics*
- *Optionally, incorporation of generalization methods, such as supervised and unsupervised learning with flight situation data*
- *Comprehensive end-to-end verification of the system in actual operation*

8. Conclusions

An important distinguishing feature of a modern aircraft can be a presence of an automated onboard flight analysis and recommendation system. The formation of recommendations is based on an integrated view of the data arriving from the environment and the internal technical state of the aircraft. These data are grouped according to the determined bundle of attributes, among which priorities are determined. For each attribute, recommendations are formed, and the actions of both the crew and the aircraft control systems are determined. In this case, as studies show, the aircraft's technical and the pilot's physical conditions are of the highest significance.

Several approaches to prioritizing the evaluation of a real-time situation were proposed, described, and analyzed. In the future generations of such systems, current techniques for modeling and analysis with uncertainty can be applied to situation assessment along the directions outlined in this work. In the view of the authors, equipping modern aircraft with such advisory systems has the potential to significantly improve the quality and reliability of individual aircraft operations as well as aerial operational networks overall.

Future research is focused on studying the problem of integrating the advisory system into the global air network and analyzing its practical value.

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Prediction of CO_2 emissions during multimodal grain transportation

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Prediction of CO_2 emissions during multimodal grain transportation

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Abstract. The article presents the results of a research on the efficiency of multimodal grain transportation from Ukraine in the global supply chains. The research was conducted on the basis of the developed simulation model. Unlike existing ones the presented model takes into account the stochastic nature of the main technological operations and delays at the intersection point of different modes of transport. Using the developed simulation models, the process of transporting grains in global supply chains from Ukraine through the Mykolaiv Commercial Port was simulated. It was experimentally determined that the environmental impact of the multimodal route is significantly lower. CO_2 emissions per ton of transported grains were 1 kg, which is almost 90 percent lower than when transported by the existing method.

1. Introduction

The main objectives of the European Green Deal are sustainable development and reduction of environmental pollution [1] to transform the EU economy into a circular economy by 2030 and achieve climate neutrality by 2050 [2]. Environmental legislation applies to various sectors, including transportation, one of the most important of which is road transport. In the EU transport market and road transport companies dominate in terms of the number of vehicles and traffic volumes [3] and at the same time it is road transport that has the largest negative impact on the environment causing more than 70 percent of all transport emissions [4].

As a result, effective incentives to reduce CO_2 emissions, improve air quality and ensure carbon neutrality in order to achieve sustainable development goals are primarily focused on road transportation. The Green Deal's policy to encourage the shift from road to rail and water transport, aimed at reducing fuel consumption, minimizing emissions of pollutants, reducing traffic intensity, and preventing road congestion, was adopted by the European Commission many years ago.

One of the policy instruments that the Commission emphasised to achieve this goal was the restructuring of the railway sectors of the Member States. The restructuring of the railway sector included market liberalisation and the creation of conditions for the development of competition between operators, primarily by creating opportunities for the emergence of new companies involved in the ownership of a fleet of wagons and locomotives and the operation of rolling stock. According to researchers, this solution is, at first glance, the least obvious political choice among the alternatives, including the Pigovian pricing system or infrastructure subsidies [5].

At the same time, the current EU transport policy aims to promote multimodal and combined transport in the Member States and third countries [6] as one of the leading means of reducing the environmental impact of transport and reducing CO_2 emissions by 20 percent by 2030 [7].

Meanwhile, the advantages of rail transport in terms of lower environmental impact compared to road transport are balanced by significant disadvantages for the shipper due to low average delivery speed, capacity and reliability [8]. At the same time, in the water transport, speed is directly correlated with the amount of fuel consumed, which is the main source of greenhouse gases. Fuel consumption per unit is a cubic function of speed, meaning that if speed increases by 10 percent, consumption will increase by 33.1 percent. As a result, higher speeds, while reducing transport time, lead to higher CO_2 emissions and increased transport costs [9]. However, currently, there are no effective tools for assessing and forecasting CO_2 emission volumes specifically for mixed (multimodal) transportation in recommendations and methodologies.

2. Problem description and method

Multimodal and combined transport as a coordinated system of several modes of transport is widely mentioned in transport policy is the subject of academic research and is used in practice to address environmental issues and overcome dependence on road transport. Multimodal transportation is defined as the transport of goods carried out by a sequence of at least two different ways [10], traditionally by road, rail and water transport [11]. Intermodal transport is a type of multimodal supply chain that involves the movement of goods in one cargo unit or vehicle and is not processed during a change of mode [12]. Multimodal transport activities, such as loading, transportation and transshipment operations, require a large amount of resources, determination of optimal route plans and cost control [13].

Route planning for multimodal transport has been studied by numerous researchers, and solutions primarily included optimization based on various criteria groups. These criteria include cost, time, safety, risk, environmental impact (CO_2 emissions), demand, and customer preferences [11, 14–18]. Inland water transport has been positioned as a priority in logistic chains due to its higher economic efficiency and lower pollutant emissions, making it more competitive [11,18]. However, the vast majority of studies have focused on multimodal transport without inland water transport, specifically involving road and rail transport [19], international port-rail transport, port-road inland transport, combined ship-road-rail transport [20] modal shift from road to sea transport [21], port infrastructure development as a multimodal logistics center based on container transport parameters [22].

The above underscores that there is a need for integrated decision support tools to optimize and solve the problems of sustainability of multimodal supply chains using road, rail and water transport.

The purpose of the research is, through experimental simulation, to provide a forecast of CO_2 emissions volumes in the multimodal grain supply chain. To achieve this goal, it is planned to:

(i) to develop a mathematical (simulation) model of multimodal grain transportation involving road, rail and water transport;

(ii) develop a methodology for assessing the negative impact of the transport sector in multimodal grain transportation.

The research focuses on the transportation of grain cargo due to the fact that Ukraine is a key player in the global food market. In the period from March 2022 to December 2023 were exported 41.6 million tonnes of corn and 24.7 million tonnes of wheat. Out of the total volume of cargo were crossed the border through ports: 73.3 million of tonnes and 18.7 million tonnes were exported by rail, and 7.4 million tonnes by road [23].

3. Results and discussion

The delivery time of bulk goods, essentially from origin points to seaport terminals, by rail and road transport, can be formalized as follows:

$$Q_{deliv} = t_{truck} + t_{rail}, \tag{1}$$

where t_{truck} is the time spent by cargo mass in the road transport subsystem, hours; t_{rail} is the time spent by the cargo mass in the railway transportation subsystem, hours.

However, each element of the expression (1) consists of two main components: the waiting time for technological operations and the time for performing technological operations (illustrated for road transport).

$$t_{truck} = t_{wait.} + t_{work.oper.}, \tag{2}$$

where $t_{wait.}$ is the total time spent by the cargo mass and vehicle on the idle time while waiting for technological operations, hours; $t_{work.oper.}$ is the total time spent by the vehicle to perform technological operations, hours.

At the same time, each of the elements of expression (1) represents a combination of two large components – time for waiting for technological operations and time for performing technological operations (using the example of road transport):

$$t_{deliv} = \sum t_{wait.} + \sum t_{work.oper.} \rightarrow \min, \tag{3}$$

with restrictions:

$$\begin{cases} \zeta_{truck} \leq \zeta_f, \\ \zeta_{truck} \leq \zeta_r, \\ \zeta_{rail} \leq \zeta_f, \\ \zeta_{rail} \leq \zeta_r, \\ n_{truck}, n_{rail}, n_{bulk} = 1, 2, 3, ...N, \end{cases} \tag{4}$$

where $\sum t_{wait.}$ is the total time spent waiting for operations in the transportation process on the entire multimodal grain supply chain, hours; $\sum t_{work.oper.}$ is the total time spent on operations in the process of transportation on the entire multimodal grain supply chain, hours; ζ_{truck}, ζ_{rail} is utilization rates of use of the fleet of trucks and railway rolling stock; ζ_f is the limit level of technological failure resistance of elements of transport systems; ζ_r is the limit level of technological rationality (expediency) in the use of elements of transport systems; $n_{truck}, n_{rail}, n_{bulk}$ are the need for rolling stock: trucks, railway routes, bulk carriers, units.

Given that most of the presented elements of the optimization model and its constraints are implicit functions of complex multi-phase processes in mass service systems under stochastic flows one of the few methods for studying could be simulation (computer modeling).

The carrier model was developed on the basis of the agent-based approach since the entire multimodal process represents a combination of independent subsystems involved in one process – the grain supply chain.

Then the following processes and phenomena will act as agents of such model (table 1).

The model was implemented using the Java SE libraries in the AnyLogic University Researcher using the example of the most typical grain supply chain from the central regions

Table 1. Agents of the simulation model of the multimodal route.

The name of model agents	Function of the model agents
Automotive subsystem	Modeling the turnover of trucks on the network. Simulation of technological processes of loading / unloading, waiting for operations, movement
Railway subsystem	Modeling the turnover of railway routes on the network. Simulation of technological processes of loading / unloading, waiting for operations, movement
Water subsystem	Modeling the turnover of cargo ships – bulkers within the global supply chain. Simulation of technological processes of loading / unloading, waiting for operations in ports, traffic
Warrant	Simulation of the preparation of an information message about the availability of a ready-to-ship consignment. This type of agent is essentially the same for all transport subsystems. The difference is that it is generated by the model under different conditions. The main condition for the generation of the message: the actual presence of a ready-to-ship grain cargo in sizes that meet the technical standards for loading, respectively, into a truck, a railway dispatch route, a bulk carrier
Cargo model	A unit of cargo generated as a random requirement in the simulation process. For this model, one ton of grain is accepted as a cargo module

of Ukraine through the Mykolaiv seaport. This freight flow is one of the key components for Ukraine's agricultural sector and continues to operate even during periods of constant shelling due to military aggression from the Russian Federation. Agent-based and discrete methods in simulating multimodal transportation have been extensively discussed in our previous studies [24].

The following results were obtained during experimental modeling (table 2).

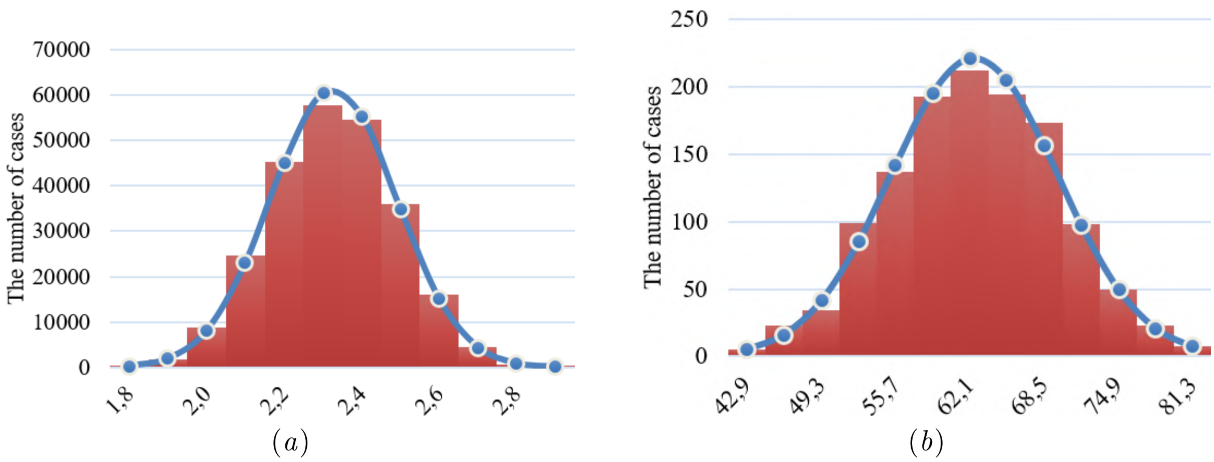

Figure 1. Experimental results. Normal density distribution of dwell time for cargo mass in the truck (a) and railway (b) transportation subsystems.

Table 2. Results of experimental modeling.

Parameter	Value	Note
Output data		
Volume of grain transportation, thousands of tons per year	1000	
Points of origin and primary concentration of cargo (the distance to the destinations was automatically calculated using GIS technology (with an accuracy of 100 meters))	Velika Viska; Alexandria; Tyshkivka; Bobrynets	
Point of departure from Ukraine	Mykolaiv Sea Port	
Received data		
Automotive transport system:		At the technical
coefficient of use of rolling stock	72 percent	loading rate
the need for rolling stock	18	of 20 tons
Railway transport system:		At the technical
coefficient of use of rolling stock	59 percent	loading rate
need for rolling stock (railway routes)	3	of 4,000 tons

Table 3. Carbon footprint levels per unit of transport work.

Indicator	Only by road (existing option)	Multimodal route (road and rail)	Difference, percent
emissions for transportation of a ton of cargo by land, kg*	12.8	1	- -92.0
emissions per 1000 ton-km, kg*	32.81	2.64	-92.0

* Under the assumption of using "clean" CO_2 emissions-free electricity.

The dwell time of one ton of cargo in the transportation subsystems follows a normal distribution, indicating sufficient resilience of the transportation process (figure 1).

The actual carbon footprint levels per unit of transport work were as follows (table 3).

4. Conclusions

An agent-based simulation model of multimodal transportation of grains involving truck, rail and water transport has been developed. Unlike existing models, the presented model maximally considers the stochastic nature of performing key technological operations.

Based on the developed simulation models, the process of transporting grains in global supply chains from Ukraine through the Mykolaiv Trade Port was simulated. As a result, it was established that the environmental impact of the multimodal route is significantly lower. CO_2 emissions per ton of transported grains amounted to 1 kg, which is nearly 90 percent lower than in the existing transportation method.

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Sustainable development of the Pirnovo community in the Kyiv region: problems and perspectives

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Sustainable development of the Pirnovo community in the Kyiv region: problems and perspectives

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Abstract. Currently, Ukrainian rural communities experience the devastating impact of war, which increases the difficulties of economic and social growth in sparsely urbanized areas. The military escalation has put on standby the processes of social infrastructure modernization, creation of peaceful jobs, expansion of local production and the development of local culture, forcing Ukrainians to focus on such problems, as increasing the stability of settlements, preserving the lives and health of their residents, and saving critical infrastructure. At the same time, preparing for the post-war reconstruction of the country, experts have to think about ways to develop recovery strategies and about further sustainable development of all regions of Ukraine. This study presents an analysis of the urban-planning and environmental challenges faced by the Pirnovo community on its way towards a sustainable future and offers ways of transforming the architectural environment in order to improve the quality of life of the local population and preserve the ecological and cultural heritage. The research methodology includes analysis of current community issues and unrealized opportunities, spatial modeling of comprehensive territorial development, development of proposals for gentrification of existing settlements, improvement of the environment through innovative technologies. The proposed comprehensive development plan allows for considering alternative options for utilizing the recreational potential of the territory, methods of modernizing the cultural and household services system for the population, and ways to achieve environmental balance. Our version of the general plan for Pirnovo focuses on necessary land management changes, development of social infrastructure, and improvement of the quality of living environment without destruction of the natural. The detailed plan of the central part of Pirnovo demonstrates possible approaches to reconstruction and creation of modern public spaces. The research offers new ways to address existing problems in specific areas that can help other settlements and rural territorial communities achieve sustainable development.

1. Introduction

Today, the development of strategies for sustainable development of specific regions [1] is becoming a priority requirement of administrative reform aimed at solving pressing problems of the rural population of Ukraine. The most important among them are the creation of additional jobs, the transformation of an outdated social infrastructure, the introduction of new technologies for local production, protection and restoration of natural environment and local culture. And during the post-war reconstruction period in Ukraine the relevance of these intentions will only grow.

A large number of international and state documents are devoted to the problems of sustainable development [2–4]. The research considered urban aspects of sustainable development [5], issues of administrative and territorial reform of Ukraine [6], problems of using the recreational potential of local settlement systems [7], approaches to preserving the traditional nature of planning and construction of historical architectural environment [8], options, creation of possible tourist and recreational facilities in rural areas and rural settlements [9], the basics of reconstruction of the central villages of the primary settlement system [10], principles of reforming the social infrastructure of the village [11], the problem of creating children's medical institutions network in Ukraine [12] and approaches to solving the issues of architectural organization of innovation parks [13]. Researchers paid much less attention to the problems of sustainable development of specific territories and communities, and the creation of a comfortable living environment for the inhabitants.

At the same time, the analysis of foreign experience proves how important the aspect of sustainable development is in the creation of residential units that will meet modern ecological, social and architectural requirements and challenges. It is necessary to support the implementation of programs and projects aimed at achieving sustainable development of rural areas. A significant number of such projects have already been implemented and proven to be a positive contribution to the achievement of sustainable development goals.

Thus, in 1991, at the initiative of the European Union, a program named LEADER was developed with funding periods to support the development of rural areas, with the aim of revitalizing rural areas and creating jobs. The program of activities is aimed at small, cohesive areas of communities. Local actors develop the concept of local development strategies, and the public and private sectors mobilize all available skills and resources to implement the strategy. LEADER is guided by the principles of innovation – the introduction of new ideas and methods, and integration between economic, social, cultural and environmental factors [14]. The program is not going to be any less relevant in the future, neither. Now all rural areas of the EU are able to use the program. The local population, organizations and institutions are trained at the local, regional, national and European levels. Cooperation between the participants of the program for the exchange of experience is also developing. This program is designed not only for building development strategies, but also achieves serious results in the practical implementation of these strategies [15].

The ReGen Villages project is a group of 100 energy-positive houses situated on 1.5 hectares on the outskirts of Amsterdam. The project offers an environmentally friendly alternative to city life. State-of-the-art technologies and business methods are combined here. For example, vertical farming and aquaponics. The concept has seven components that will make each home completely self-sufficient: House, greenhouse, aquaponics, seasonal garden, animal husbandry, solar panels, water storage. home, greenhouse, aquaponic, seasonal garden, livestock, solar cell, water storage. The settlement is self-sufficient and sustainable and meets almost all 17 UN Sustainable Development Goals [16].

The Crystal Waters Permaculture Village in Australia – the world's first permaculture village – was founded in 1984. The community has more than 250 residents, being a unique and sustainable village. The houses use solar energy and collect rainwater. The village is located next to a wildlife reserve in the scenic Conondale Valley, so on the way you can see kangaroos, wallabies and other wildlife species that coexist beautifully with the residents. The settlement is based on permaculture principles and offers a wide range of activities: an organic wood-fired bakery, monthly markets, music events, Friday movies, permaculture and sustainable living classes, the community includes a Crystal Waters eco-park, with camping sites [17].

Since 2016, the Rural Habitability program has been operating in Chile, improving the lives of the rural population. Rural life in Chile was unfortunately characterized by poor quality, overcrowded houses, lack of electricity, efficient heating and sanitary conditions. So, the Chilean government announced the Emergency Housing Plan. The program provides funding and technical support to people in rural communities. New energy-efficient houses are being built, existing houses are being improved. Special attention is paid to vulnerable groups, indigenous people and households headed by women. Thanks to the program, it was possible to reduce the migration of the rural population to large cities, which is of serious importance for the Chilean economy [18].

This study is devoted to a local territory in the suburbs of the capital of Ukraine that belongs to the Pirnovo territorial community. Among the acute problems of the Pirnovo community are seasonal fluctuations in population, lack of jobs, chaotic development of settlements, destruction of reserves, lack of waste sorting and a recycling system. However, the area has a favorable location and has significant recreational potential.

The purpose of this study is to analyze the strengths and weaknesses, opportunities and threats, risks and challenges to be considered in forecasting urban development of Pirnovo community in Kyiv region, as well as in the theoretical justification and development of project proposals for restructuring and renovation. Architectural environment of the administrative center of the community – the village of Pirnovo, aimed at improving the quality of life of the local population.

2. Methodology

Identification of the peculiarities of historical development and the current state of the territory, which today belongs to the Pirnovo community, in this study was carried out using the methods of historical analysis and field survey. Historical analysis involved examining archival documents, historical maps, and scholarly literature to trace the evolution of the territory from ancient times to the present. Field surveys were conducted to assess the current state of settlements, infrastructure, and natural resources within the community.

Methods of SWOT analysis and structural-logical modeling were used to analyze current problems and unrealized opportunities of the community. The SWOT analysis identified the Strengths, Weaknesses, Opportunities, and Threats facing the Pirnovo community, providing a comprehensive assessment of its internal and external factors. Structural-logical modeling was employed to visualize the relationships between these factors and to develop a conceptual model of sustainable community development.

Methods of spatial-territorial and project-planning modeling, as well as experimental design were used to form project proposals for adjusting the integrated development of the community, restructuring existing settlements and improving their architectural environment. Spatial-territorial modeling involved creating digital maps and 3D models of the community's territory to analyze land use patterns, infrastructure networks, and ecological systems. Project-planning modeling was used to generate alternative scenarios for the functional zoning and spatial organization of settlements based on the principles of sustainable development.

Experimental design techniques were applied to test and refine these scenarios through participatory workshops with community stakeholders. The resulting project proposals were visualized using a combination of 2D drawings, 3D renderings, and physical models to effectively communicate the vision for the community's sustainable future to decision-makers and the general public.

3. Results

3.1. Peculiarities in historical development of present-day Pirnovo community

The Pirnovo community is located in the northern part of the Kyiv region and is part of the Vyshhorod district. The community consists of ten villages: Novosilky, Lebedivka, Nyzhnia Dubechnya, Vyshya Dubechnya, Voropaev, Zhukin, Rovzhi, Bodenki, Suvid, and the territorial center of Pirnovo, located 28 km northeast of Vyshhorod and 48 km from Kyiv.

The total area of the community is 72760 hectares with a population of 6233 thousand people as of 2021 [19]. Most of the territory has a gentle relief. The Desna River flows through the north-eastern part of the territory, and the Kyiv Reservoir is located in its north-western part.

The beginning of digest of the area currently remains unclear. In the lands between the villages of Suvid, Zhukin and Voropaev, cultural heritage monuments related to the Bronze Age, Kievan Rus' and the late Middle Ages were found. There is a legend about the founding of the village of Pirnovo by ancient Russian princes, who stopped at this place and "feasted" ("to feast" in Russian: "pirovat"), which suggests that this ancient Slavic word is where the name of the village Pirnovo is derived from.

It isn't just the legend hat testifies to the stops of the princes on this terrain, but also the study of the lower Desna terrains, during which five differently dated sites of the Bronze Age were found near the village of Zhukin and between the villages of Zhukin and Voropaev. In the chronicles "Teachings of Volodymyr Monomakh" the Kyivan prince recalls that during his reign in Chernihiv he had to ride more than 100 times back to Kyiv to the summons of his father, the Grand Duke of Kyiv Vsevolod Yaroslavych, and that he rode "from morning to evening" [20]. Archaeological explorations have made it possible to specify the prince's route along the Desna. Along his route he passed a number of settlements and villages, where replacement horses were kept, without which such a high-speed journey would hardly have been possible. The location of modern settlements of the Pirnovo community coincides with the location of the settlements on the Monomakh's "Chernihiv – Kyiv" route [21].

In the time of the Russian Empire, the contemporary community's lands were part of the Oster County of the Chernihiv Province. According to county documents, Russians, Belarusians, Germans, Poles and Bashkirs lived here. During the October Revolution, confrontations between various social groups began in these territories as well. With the advent of Bolshevist power, wealthy citizens were repressed. In later Soviet times however, cultural and educational activities were actively carried out.

The village of Pirnovo itself is very young. The first written mention of it is contained in the "List of settlements of Kyiv districts" and dates back to 1926. Then this area was called Pirno tract. In 1926, a country settlement appeared there. During the temporary Nazi occupation in the village of Pirnovo were located resorts of the National Socialists.

The Germans began to develop the village. During their stay on the territory, a number of facilities was built: a water tower (which still serves as the village's calling card), administrative buildings, a prison and a hospital building. Facilities built during the National Socialist era are still in use.

The consequences of the Second World War were mass graves and lost settlements. Entire villages such as Zhukin, Voropaev, Suvid, Novosilky and Nyzhnia Dubechnia were destroyed by fire at the hands of criminal groups. Such gangs' intimidated locals, organized sabotage, and banned dialogue between the local residents and Soviet officials. These events are evidenced by the scientific works of Philip Warren on Nazi occupation security in Eastern Europe and Soviet Russia in the period from 1942 to 1945 [22].

In the postwar years, due to the large number of people with injuries after the war, the medical industry was actively developing. Professionals and the entire Union were distributed among hospitals, outpatient departments and tuberculosis dispensaries. In 1957 a hospital was opened in Pirnovo. Intensive resettlement of residents began – people returned from the war, from camps, or simply came here from other places due to complete destruction of their own homes, villages and towns.

In the 1950s, the area was connected to the grid. Electrification has given rise to the development of industrial facilities, collective farms, cultural, educational and health facilities. A new state system is formed, the Pirnovo district appears. Pirnovo is becoming a district center, infrastructure is developing. In addition, there is a butter factory, school, kindergarten, cinema, house of culture, market, road department, military enlistment office, open-air summer cinemas, Dynamo Stadium, a number of recreation centers, shops, own bakery, poultry farm, lemonade factory, TV studio, forestry, hunting, post office, a large number of cafes, river port, airfield direction Zhulyany – Pirnovo, a bus station and the Pirnovo Ornithological Reserve.

Pirnovo doesn't just become the district center, but also a tourist magnet. The village includes several recreation centers: "Rozdollya", "Slavutich", "Desna" (exit to the second beach of the sleeve), "Voskhod", "Druzhba", and "Chaika". In the direction from the center of Pirnovo towards Desna, near the ornithological reserve there are recreation centers "Leleka" and "Dynamo" (near the football field). The architectural and planning structure of the village on the peninsula is formed mainly along the old transport routes: from the ferry to the land routes that connected the route Chernihiv – Vyshgorod – Kyiv. The main planning axis extends perpendicularly from the regional highway R-69 Kyiv – Chernihiv towards the forest and continues up to the Desna.

The accents in the composition of the village are the territories of recreation centers, while the rest of the buildings are ordinary and clearly structured on a hippodame grid. The features of the village's landscape and spacial structure is due to landscape and recreational factors. In the 1970s, the population density during the holiday season was very high, as tourists came from all over the Soviet Union to admire the picturesque banks of the Desna and enjoy their holiday.

Other villages of the Pirnovo district were characterized by another sphere of activity: collective farms and other agricultural structures were located in these territories. For instance, the village of Nyzhnia Dubechnya was engaged in cattle breeding, there was a dairy farm, Zhukin is famous for beekeeping, the village of Novosilky was famous for apple orchards, and Voropaev – for machine building. Accordingly, the planning structure of these settlements is very different from the district center, with more chaotic buildings, manor-type dwellings at a great distance from each other and are hectares of fertile land between them.

In the 90's production stopped completely, there was a change of owners and officials, and a total redistribution of land. The area has stopped providing quality tourist services, although ever since people have still been coming here for vacation, mostly from Kiev and surrounding areas.

Unfortunately, the beginning of the 21st century for the village of Pirnovo was marked by complete anarchy and decline. The sale of about 5 hectares (more than half) of the gray heron ornithological reserve has led to the destruction of centuries-old oaks and pines, the destruction of its ecosystem. Although bird nesting has declined significantly, the gray heron is still returning to the reduced reserve. During this period, the territories of collective farms fell into disrepair, a significant part of agricultural land was illegally taken away from residents, and there was an illegal change in the purpose of land.

In 2014, a master plan was developed with. Pirnovo, who ignores the legal and planning restrictions of the territory [23]. In 2020, the master plan of Pirnovo was declared invalid by a court and in gross violation of the laws of territorial planning [24].

3.2. Analysis of the modern use of the community's territories

In order to assess the current problems and the potential for further development of the area, we studied some aspects of economic, social and cultural life of the Pirnovo community, as well as the convenience of transport links and available resources of the nature reserve fund.

BUDGET-FORMING ENTERPRISES : INDUSTRIAL AND AGRO-INDUSTRIAL ENTERPRISES	
1. ROVZHI	HUNTING AND FISHING BASE: «NEPTUN», «EBIS»
2. SUVID	WOODWORKING
3. BODENKI	MEDICAL AND OBSTETRIC STATION
4. ZHUKIN	GROWING CEREALS & MEAT PRODUCTION «AGROMARS COMPLEX»
5. VOROPAEV	WOODWORKING (FIREWOOD) TIRE FITTING
6. PIRNOVO	HAIR COSMETICS & PERSONAL CARE «COMBI» FORESTRY / WOODWORKING / BREWERY/
7. VYSHYA DUBECHNYA	COW & GOAT FARMING / PIG BREEDING / GROWING CEREALS/SALE OF PLASTIC PRODUCTS
8. NYZHNIA DUBECHNYA	MANUFACTURE OF FOOTWEAR, MIXED AGRICULTURE GROWING VEGETABLE AND GARDEN CROPS
9. NOVOSILKY	SYNTHETIC LEATHER & NEEDLECRAFT FABRIC GROWING VEGETABLES, FRUIT, BERRIES AND GRAPES
10. LEBEDIVKA	FISHERY / RESEARCH AND DEVELOPMENT OF NATURAL AND TECHNICAL SCIENCES / MANUFACTURE OF SEWING PRODUCTS

(a)

BUDGET-FORMING ENTERPRISES : NOMBER OF RECREATION CENTERS	
1. ROVZHI	3
2. SUVID	1
3. BODENKI	
4. ZHUKIN	2
5. VOROPAEV	2
6. PIRNOVO	8
7. VYSHYA DUBECHNYA	1
8. NYZHNIA DUBECHNYA	
9. NOVOSILKY	2
10. LEBEDIVKA	2

(b)

Figure 1. Budget-forming enterprises of the Pirnovo territorial community: a) industrial and agro-industrial enterprises, b) recreation centers.

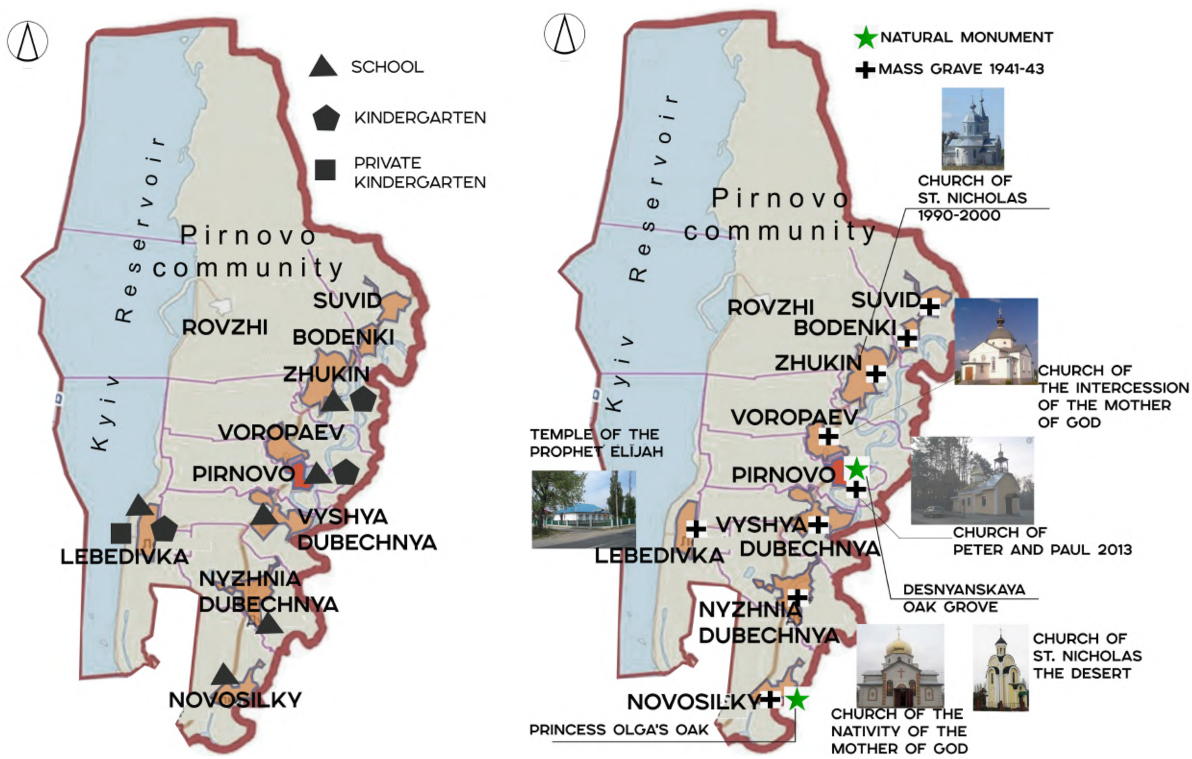
Thus, figure 1a shows the most powerful productions, which are “Vyshchedubechanske forestry”, “Agromars Complex”, farms for growing fruits and vegetables, berries and grapes.

Another powerful budget-generating source of the community is the area’s recreational resource. Figure 1b shows the number of recreation centers in different localities. It turned out that the village of Pirnovo, the community center, has the largest number of territories set aside for recreation.

Figure 2a shows the institutions of preschool and secondary general education. As can be seen, there are 9 educational institutions on the territory of the community, mostly state ones, but there is also one private preschool institution.

Figure 2b shows sites of historical and cultural value. Unfortunately, there are no monuments left in this area that would have a protected status. There are only monuments of local significance, namely: monumental art at the Common Graves, the monument to I. P. Pavlov on the territory of the hospital in the village of Pirnovo. There are also religious buildings, in particular, six churches of the Orthodox rite.

Socio-demographic analysis of the population showed that the area is inhabited by Ukrainians, Russians, Jews, Georgians and Armenians. According to official data, the number of people registered in the territory is 6764. However, there is a problem of counting the real population, because the territory of the community is inhabited not only by villagers but also by urban citizens. There are a large number of private country houses, cottage villages, wealthy residences and health resorts. As a result, a large number of vacationers come here during the holiday season. This provision is evidenced by the cadastral map of Ukraine, master plans of villages, and personal experiments to monitor capacity. Also, the events of recent years related to the



(*a*) (*b*)

Figure 2. Some aspects of social and cultural life of the Pirnovo community: a) educational institutions, b) historical and cultural monuments and religious buildings.

coronavirus epidemic have shown that the population of Kyiv is rapidly moving to suburban settlements. This is possible due to the small distance from all settlements of the Pirnovo community to the capital of Ukraine.

The analysis of the nature reserve fund confirmed the significant recreational potential of the analyzed area. The community includes the ornithological reserve "Zhuravlyny" and the reserve of the gray heron "Pirnovoskyi", the landscape reserve "Dniprovsko-Desnyanskyi" and "Chernynskyi" (figure 3). As of 2016, the Kyiv Reservoir was included in the "Emerald Network", a large area of which was included in the Pirnovo community. The Emerald Network is an area that contains rare and very valuable plant and animal habitats [25]. To date, the Emerald Network at the level of Ukrainian legislation exists in a contradictory state, although information about it can already be obtained in free access on the cadastral map [26].

Documents certifying the priority of the resort and tourist-focused of development of the studied community have recently been prepared. In particular, the decision of the Kyiv Regional Administration of October 15, 2020 "On official approval of the recognition of natural areas of the Pirnovo community as a resort area of local importance" [27] provides for further development of tourism development programs, health resorts, specifically in this area, within Pirnovoska communities. Such a project is funded by the state and creates an attractive investment climate.

Another encouraging signal is the discussion of an action plan for the development of medical tourism in the Kyiv region. This is noted by KODA and the Association of Medical Tourism in Ukraine. Due to the fact that a large number of resorts and medical institutions are located in the region, it became possible to develop medical and tourist activities on the territory [28]. Such projects contribute to the popularization of the region and the development of rural areas. This will help reduce unemployment in the country. New jobs, in turn, will keep people from looking for a better life abroad.

The analysis showed that over the past ten years there has been a revival of the economy of the Pirnovo community, and the interest of investors in the development of the territory is growing. At the same time, in order to move to a qualitatively new level of development and completely restore the community after the decline, it is necessary to use the hidden opportunities of this area, open it and make it attractive to investors by developing and diversifying the economic complex, involvement in the economic turnover of the resource potential of all settlements of the community. The opportunity for sustainable development of the Pirnovo community can be ensured through significant reserves of forest resources, promising development of tourism and recreation, and the use of innovative recycling technologies.

3.3. Proposals for restructuring the territory of the Pirnovo community

Proposals for community development are based on five resource-oriented subsystems: "Population", "Infrastructure", "Production", "Nature" and "Heritage".

Subsystem "Population" is among the leading ones and determines the parameters and organization of other subsystems. The infrastructure subsystem includes housing, social, and engineering and transport components. The subsystem "Production" unites the workplaces of the population. The subsystem "Nature", on the one hand, is the basis of the rural region, and on the other – establishes the resort and tourist direction of its development. A special role belongs to the subsystem "Heritage", which determines the individuality of the formation of spatial planning structure of the rural community (figure 4).

In order to obtain an expanded description of the Pirnovo community, a SWOT analysis was carried out which revealed the internal and external factors of land development that belong to it. The internal factors influencing the state of the territories include strengths and weaknesses. Strengths of the area are transport accessibility, a complex of water bodies (Kyiv Sea, Desna River, lakes); attractive landscape and recreational areas, biodiversity. Weaknesses of the area are neglected territory, lack of tourist infrastructure, unsatisfactory state of social, transport,

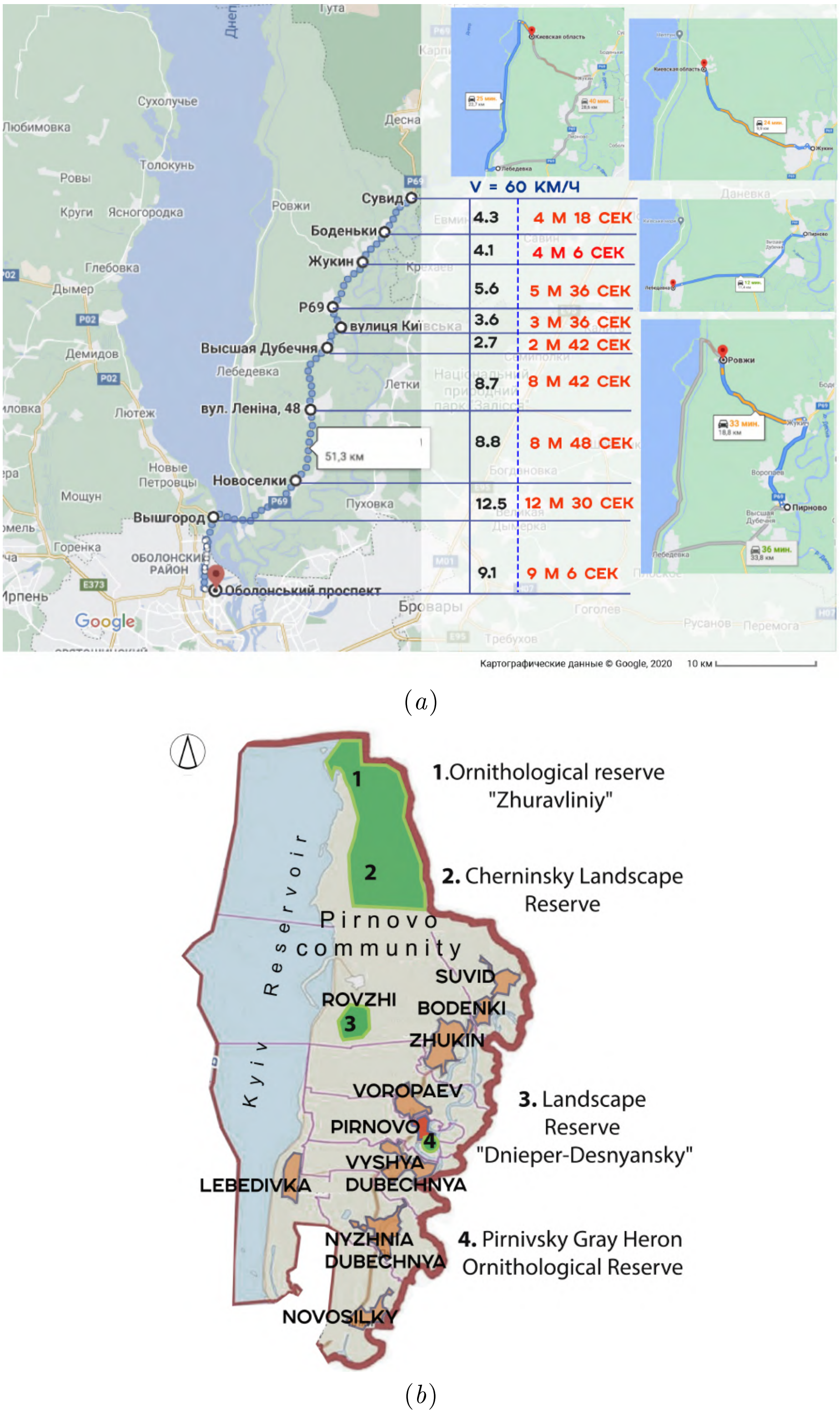


Figure 3. Analysis of transport connections and nature reserve fund of the Pirnovo community: (a) written in red is the time of movement by motor transport between settlements, (b) areas of the nature reserve fund.

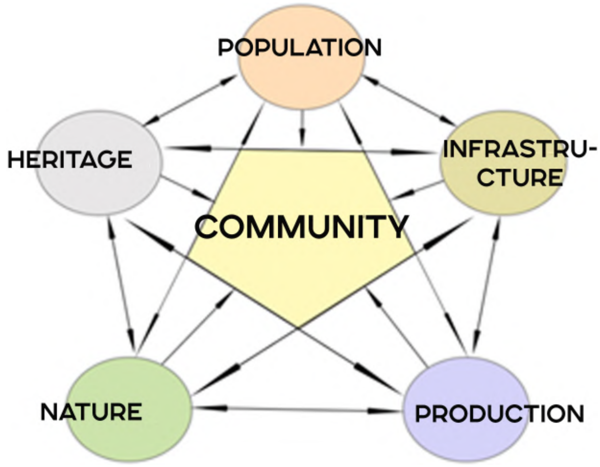


Figure 4. Five resource-oriented subsystems for the development of the Pirnovoska community.

and engineering infrastructure.

External factors include potential opportunities and threats to the stable development of the analyzed areas. Opportunities – revival of nature reserves, interest in tourism development (festivals, fairs), rational use of recreation areas (development of a network of rehabilitation facilities for persons affected by the war), introduction and promotion of advanced technologies of agro-industrial production, craft technologies, IT technologies and recycling technologies, providing of decent conditions for temporary residence of internally displaced persons and increasing the attractiveness of areas by improving the quality of life of locals. Threats – the devastating consequences of the war, manifested in the constant killing and maiming of people, the destruction of residential buildings, public buildings, industrial enterprises, engineering and transport infrastructure, the contamination of agricultural lands, recreational areas and water bodies with harmful substances and explosive objects, changes in the demographic structure of the population, interruptions in the provision of electricity and many other challenges that multiplied the pre-war troubles, including: the impact of the pandemic, unstable situation in the country, lack of sufficient funding, instability of the legislative sphere, destruction of green spaces, as well as lack of initiative of a large part of residents.

The conducted analysis suggested the basic features for the model of sustainable development of the Pirnovo community, which will help transform the weaknesses into strengths, and threats into opportunities (figure 5). The compiled model highlights the key functional and planning elements of the community and sets out proposals for the formation of new types of entrepreneurial activity. The main functional areas include residential, production(working), recreational and communal storage areas, as well as areas of hotel industry and retail. The production(working) zone is supposed to include budget-generating enterprises of touristic, recreational, medical, wellness, economic and industrial nature, the formation of which should contribute to achieving the main objectives of sustainable development of the Pirnovo community and the territory belonging to it.

The proposed model allowed to determine the priority areas of activity of local residents and became the basis for drawing up a comprehensive plan for spatial development of the Pirnovo community with specific proposals for the reorganization of rural areas (figure 6). This plan was developed on the basis of a comprehensive assessment of areas, taking into account the cadastral map, current planning restrictions, existing transport infrastructure and landscape plan of community areas. The complex plan of spatial development of the Pirnovo community includes drawings of general plans of settlements with existing buildings, and adjacent territories

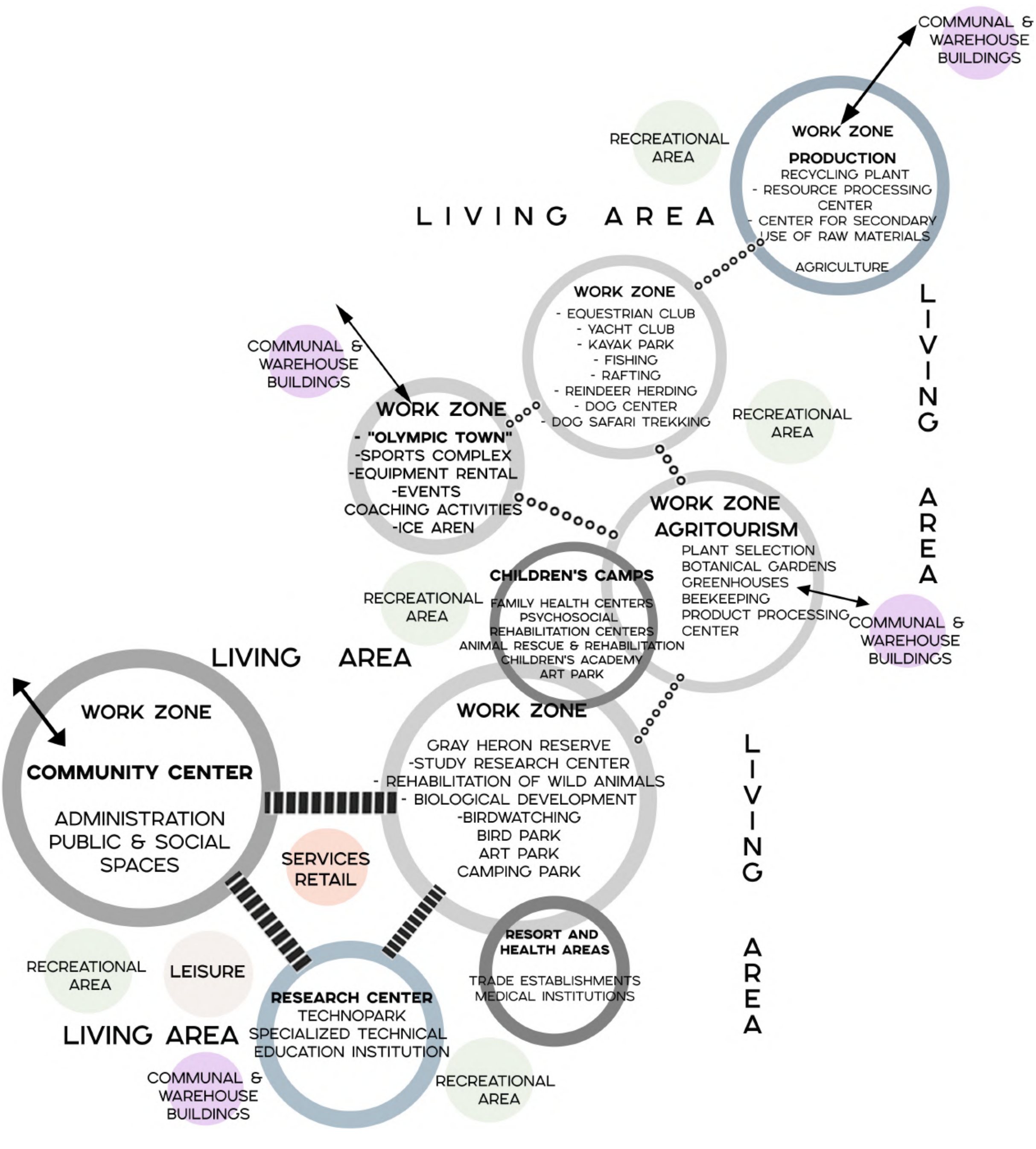


Figure 5. Model of sustainable development of the Pirnovo community.

of the community, separately defined areas of reserves. New ideas for the development of the existing resettlement system include the separation of the “working zone” of each settlement. The list of budget-generating enterprises included in these territorial and spatial elements is determined by the availability of the best conditions for their development in their locations.

In particular, in the western part of the community it is proposed to support sports and recreation. To do this, from the side of the Kyiv Reservoir, south of the village of Lebedivka to create an “Olympic Town” with a sports complex for events and training in ice sports, north of the village of Lebedivka appropriate to organize a yacht club, a kayak park and rafting routes. In

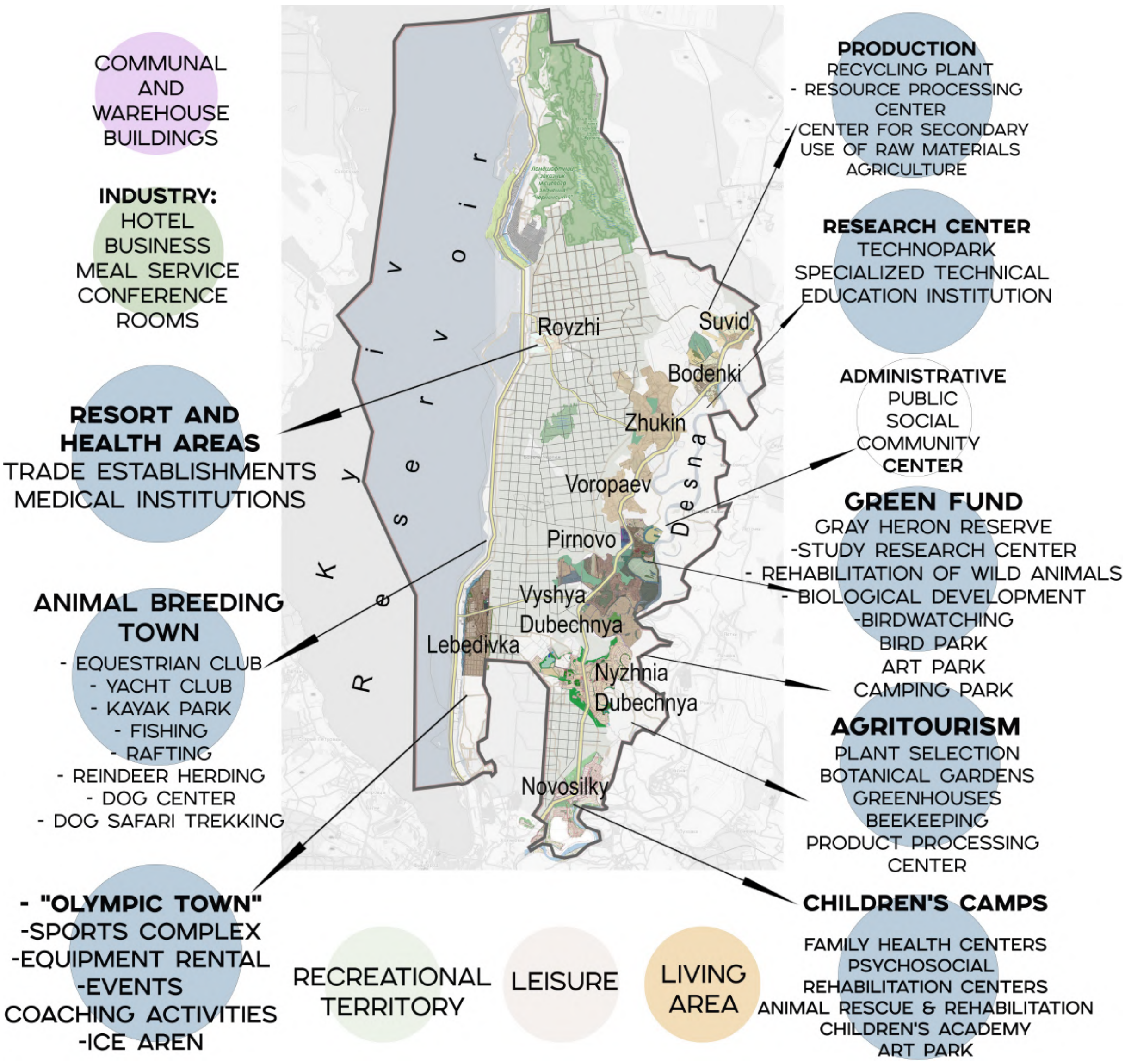


Figure 6. Comprehensive plan of spatial development of Pirnovo territorial community of Kyiv region.

the village of Rovzhi, it is proposed to build a “Retreat Town”, which will include health resorts, medical facilities, tour organization and touring facilities. The eastern part of the community – the village of Vyshya Dubechnya – might be turned into an “Agrotourism town” with complexes of plant selection, a botanical garden, greenhouses, apiaries and centers of processing of agricultural products. In the southern part of the community – the village of Novosilky, it is planned to create a “Family Town” with children’s camps, family health and psychosocial rehabilitation centers, animal rescue and rehabilitation centers, a children’s academy and an art park. The village of Zhukin is supposed to become an “Animal Breeding Town” with equestrian club complexes, fishing ponds, reindeer herding grounds, a dog training center, a dog breeding facility for service and sports purposes, as well as dog safari trekking routes. The village of Voropaev should be equipped with a “Technopark”, which will include a research center and a specialized technical education institution. In the northern part of the community – near the village of Suvid – it is proposed to locate a "Center of production activities" with a waste sorting station, waste processing plant, enterprise for processing resources and recycling, as well as a center for automation and robotics of agriculture. Finally, it is proposed to turn the village of Pirnovo into the center point of the community – the "Community's Green Fund", which will include a restored ornithological "Gray Heron Reserve", wildlife rehabilitation centers, wildlife research and biological development, birdwatching centers, a bird park , an art park, and a camping park. Tourists accompanied by a guide will be able to visit the Chernynsky and Zhuravlyny Reserves, which are located in the very north of the community.

The next step on the way towards sustainable development of the Pirnovo territorial community should be to determine the necessary measures for the transformation of individual settlements. The peculiarities of this stage can be shown by drawing out a clear strategy for the main settlement of the community, the village of Pirnovo. To provide a sustainable development strategy of Pirnovo it is necessary to define the requirements for the transformation of the settlement and the formation of a model of its harmonious organization with further development of the project of territorial and spatial development of the village, with specific proposals, restoration of favorable hydrological regime and sanitary condition of the Desna and general improvement of ecological conditions of the territory.

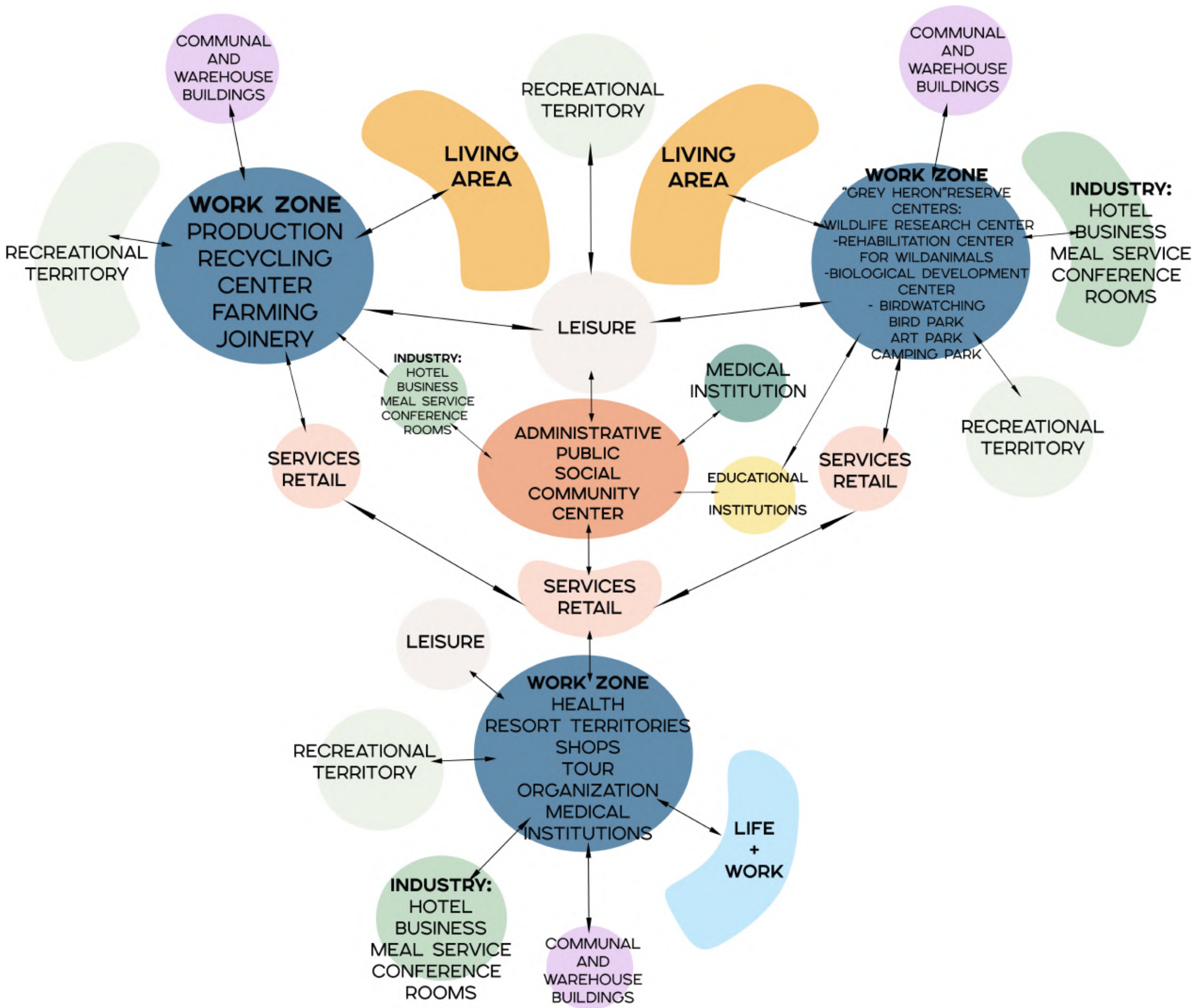


Figure 7. The model of sustainable development of the village of Pirnovo, Kyiv region.

The model of sustainable development of Pirnovo clarifies the composition and location of the village's main functional areas, as well as the presence of the necessary planning links between them (figure 7).

Based on the proposed model, an alternative master plan for the village of Pirnovo was developed, which, unlike the existing one [23], which has actually never been officially approved, takes into account land ownership, functional purpose of land according to land cadastre, and current state building codes in Ukraine (figure 8).

At the final stage of their work, the architect must record their ideas on the formation of the village's imagery and the restoration of its aesthetic appeal. In this study, we drew attention to the need to reconstruct the central part of the village. The artistic concept of the settlement's architectural environment transformation was to develop a comfortable, modern community center which will meet the goals of sustainable development that will not harm the natural

Figure 8. Materials master plan of the village of Pirnovo, Kyiv region scheme of cultural and household services (left), scheme of planning decision (right).

Figure 9. Reconstruction project of the Shevchenko Boulevard in Pirnovo, Kyiv region.

environment (figure 9).

The project provides for a clear functional zoning, development of the historically formed central planning axis of the village, and filling it with all the functions that the community needs. Staying in this area will allow to implement a variety of scenarios of human behavior in the architectural environment. The territory will be visited by residents of different ages, employees of nearby public services and tourists.

Different groups of the population will find here convenient and interesting areas for recreation and active leisure. Implementation of proposals for the reconstruction of the central part of the village of Pirnovo involves a number of special measures for engineering preparation of the territory (vertical planning, lowering the groundwater level, compliance with sanitary gaps, flood protection, etc.). Reconstruction of existing buildings and construction of new ones involves the use of modern energy efficient technologies. Improvement of renovated public spaces should be carried out using recycled materials.

4. Conclusions

Based on historical and SWOT analysis, structural-logical territorial-spatial and project-planning models have been developedin order to implement the principles of sustainable development of Pirnovo territorial community by monitoring urban planning, public service system, organization of engineering and transport infrastructure, and other less mobile groups, environmental protection, as well as the preservation of immovable cultural heritage sites and archeological monuments and the traditional nature of the environment of settlements.

The results of the analysis and modeling were used in the process of experimental design of the Comprehensive Spatial Development Plan of the Pirnovo Territorial Community of Kyiv Oblast, the General Plan of its administrative center – the village of Pirnovo, and the Detailed Plan of the territory of the central part of this settlement. These proposals are aimed at the primary post-war recovery steps of the studied territory and the achievement of quite realistic goals considering its sustainable development, related to the balanced economic and social growth of the territorial community, the reproduction of ecological balance and the further development of local culture.

The proposed comprehensive approach in the post-war period can be applied in other regions of Ukraine and become the basis for managing their functioning and recovery, taking into account the tasks of sustainable development for settlements and communities. This will increase the effectiveness of activities related to the implementation of the state‘s strategic goals, as well as solving local problems – planning rural areas, improving the quality of the architectural environment of settlements, a harmonious combination of artificial and natural surroundings, which will contribute to overcoming the destructive consequences of war and the further development of the capital region.

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The degree indicators of coal metamorphism for predicting the coal seams hazardous properties during the mining

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Abstract. Metamorphic processes in natural conditions reached a certain stage of the original organic matter transformation at temperatures no more than 650 °C. Analyzes of the coal physical and chemical characteristics are carried out at higher temperatures. Thermal decomposition processes determine the properties of coals during their further transformation, which is important for establishing their consumer properties. The quantitative and qualitative composition of the formed volatiles is not directly related to the fluids, previously removed from coal seams in natural conditions. The thermal decomposition products of coals are the result of a new stage in the initial organic matter transformation. It is shown that the method for determining the yield of volatile substances on a ash-free dry mass when establishing technological properties does not reflect the state of coal seams in natural conditions. Analysis of the results indicates that at present there are no methods for complete the coal sample demineralization. Obtaining an accurate value for the yield of volatile substances per ash-free dry organic mass leads to an overestimation of this indicator. Significant differences in the balances between the metamorphic processes occurring in coal seams and during the thermal decomposition of coal are caused by different conditions for their determination. The products assignment of thermal decomposition processes to a ash-free dry organic mass according to industrial classifications doesn't allow to use of their consumer properties indicators to characterize the hazardous properties of coal seams in natural conditions. It is proposed to develop the basic principles of the methodology for predicting the hazardous properties of coal seams based on the deviation of the content of organic matter main components, including moisture and sulfur, from their average indicators.

1. Introduction

Metamorphic changes in fossil coals proceeded mainly under the influence of temperatures and pressures that developed in the earth's crust as a geological processes result [1]. They boil down to enrichment of organic matter with carbon and depletion of other components. The chemical composition of coal largely determines the hazardous properties of coal seams: gas content, outburst hazard, spontaneous combustion, coal dust explosiveness and other negative phenomena. To clarify the mechanism and conditions of their occurrence, it is necessary, at least, to know the changes in the initial composition of fossil coals under the influence of these factors.

Most researchers recognize that of all the factors of metamorphism, temperature has the greatest influence [2, 3] Knowing the transformation temperature of an initial organic mass and a composition of a resulting substance, one can judge the ongoing chemical transformations of fossil coals. Based on the experiments, it was concluded that the temperature boundary between the formation of brown and hard coals is in the range of 300-325℃. The transition from coal to anthracite is possible at least at 500 ℃. Anthracite formation took place at a temperature of 500-650 ℃ [4].

The transformation of an original organic matter of fossil coals consists in increasing the carbon content (possibly up to 100 %) and reducing other components to practically zero. This trend in compositional changes with an increase in the degree of metamorphism is confirmed by the results of coals analysis from different basins [5]. The change in an elemental composition of the initial organic matter is one of the main characteristics of the metamorphic processes manifestation. The principles of determining an metamorphic transformations degree of coals by the elemental composition of organic matter are not observed in the regulatory framework [6–8], regulating the safety of mining operations. As the main indicator of metamorphic transformations of coal seams, the release of volatile substances on dry ashless organic fuel mass during a coal thermal decomposition without air access is taken (V^{daf}). This indicator and some others were borrowed, without proper scientific justification, from industrial classifications used in different periods [6].

Metamorphic processes in natural conditions reached a certain stage of the original organic matter transformation at temperatures no more than 650℃. Thermal decomposition according to the requirements [9] is carried out at 900℃for 7 min. In the first case, an organic matter during a certain geological period was in a certain pressure and temperature regime. As a result, the coal raised to the surface is characterized by a mineral association, which is inherent in conditions of high temperatures and pressures. Its stability and safety is largely determined by the previous transformation conditions. In the second, this association undergoes a change at higher temperatures. Thermal decomposition processes determine the coals properties during their further transformation, which is important for establishing their consumer properties. The quantitative and qualitative composition of the formed volatiles is not directly related to the fluids previously removed from coal seams in natural conditions. The products of coal thermal decomposition are the result of a new stage in the transformation of an initial organic matter. An example of the different stages of coal conversion, raised to the surface, are the methods for determining their suitability for producing coke and semicoke [10]. Different temperature regimes in this case determine the formation of different products of thermal decomposition, the quantitative and qualitative composition of volatile substances. (V^{daf}). This proves that coals metamorphism and their thermal decomposition are different forms of organic matter transformation, and the resulting chemical compounds differ significantly in qualitative and quantitative compositions. For this reason, the hazardous properties of coal seamsmust be predicted by indicators whose values are directly a consequence of the impact of metamorphic processes, and not the result of thermal decomposition of already converted coal.

Volatile matter yield is widely used to characterize the technological properties of coal. For these purposes, it is customary to determine V^{daf} on a dry ashless mass. This is important for calculating the yield of coke oven gas and chemical products during coking coal. Volatiles are formed from organic matter and mineral impurities. Their total amount released during thermal destruction of coals largely depends on their ash content: the higher it is, the more distorted the V^{daf} value. With an increase in ash content, the proportion of volatiles matters from mineral components increases and organic matter, to which V^{daf} belongs, decreases. Due to the lack of complete demineralization methods, the exact V^{daf} value cannot be determined in a laboratory way [4, 10, 11], and the conversion of volatile substances to organic matter leads to an overestimation of the indicator. The existing method for determining V^{daf} only approximately characterizes the behavior of the coals organic mass during thermal destruction and is completely unacceptable at a high ash content of the sample [12]. In addition, the V^{daf}

composition does not take into account the presence of moisture in the original coal samples, which has a significant effect on the condition of coal seams during mining operations.

The above facts indicate that the V^{daf} indicator was developed only to establish the consumer properties of coals and it does not characterize the degree of seams transformation at different stages of their metamorphism. Its use to determine the hazardous properties of coal seams is not sufficiently scientifically substantiated. In this regard, there is a need to improve the regulatory framework in terms of ensuring the safety of mining operations. Research in this direction is relevant, since the reduction of accidents and injuries in coal mines largely depends on their results.

Purpose of the study is to establish a set of basic indicators of the degree of metamorphic transformations of coal seams, which determine the manifestation of their dangerous properties during mining operations.

2. Results

Research methodology was developed based on the results of an analysis of currently known indicators of the degree of metamorphism of coals and scientific justification for their possible use to characterize the hazardous properties of coal seams.

Most indicators of fossil coals are designed to reliably establish their calorific value and coking capacity. For these purposes, at different times, the indicators of coking capacity (K), the yield of volatile matters (V^{daf}), the carbon content in organic matter (C_0), the presence of analytical moisture (W^a) and brand identity (M) were used. Each of these indicators characterizes one of the many aspects of the metamorphic processes of the original organic matter transformation. To varying degrees, they are mutually correlated with each other, which do not exclude some duplication in assessing the technological properties of coals. The effectiveness of using this indicators set for assessing the consumer properties of coal is beyond doubt. This is confirmed by the constant improvement of industrial classifications. Now, the classification of coals by their genetic and process parameters [7] is the most perfect. In addition to V^{daf}, R^0, V_v^{daf}, $lg\rho$, and y, it uses 6 more classificatory parameters are applied. The main of them is an average reflectance of vitrinite. As distinct from V^{daf}, R^0, V_v^{daf}, $lg\rho$, and y, the limits of its alterations are established for the whole range of metamorphism series of fossil coals as per their ranking.

It is not possible to improve the regulatory framework for the safe mining of coal seams, in which the yield of volatile during the coal thermal decomposition (V^{daf}) is used as the main indicator, for several reasons. The main one is the thermal decomposition of coals, in essence, is a modern artificial stage in the continuation of the coals transformation that occurred in earlier geological periods. The method for determining V^{daf} on a dry ashless mass does not take into account the influence of the presence of moisture and mineral impurities on the actual chemical-physical state of coal seams.

The need to establish an indicators set of the degree of coal seams conversion is dictated by the lack of consensus on the use of individual indicators in solving engineering problems. In most cases, some indicator that is not directly related to the coal seams transformation is assigned an absolute role in establishing the stages of metamorphism. A priori, one indicator can characterize only one side of the change in composition or properties during metamorphic processes.

Conventional coal grades, established for their industrial use according to the V^{daf} indicator, are taken as a criterion for general metamorphism in determining the dust-generating capacity of coal seams [6, 13]. Similarly, the strength properties of coals [14] and the propensity of seams to outburst hazard [15, 16] are assessed by their brand identity.

The danger of anthracites spontaneous combustion is made dependent on the logarithm of the specific electrical resistance. In another case [6], the propensity of seams to spontaneous combustion was determined by the interrelated V^{daf} and coal grades (M). In addition to them, a carbonation indicator has been introduced. It partially takes into account the change in the composition of organic matter with an increase in the carbon elemental content (C_0) and a decrease in hydrogen (H_0) and oxygen (O_0). Vdaf parameter adequately describes orders of bituminous coals, but there are some uncertainties in determination of boundaries between grades and sub-grades. For example, for coals of 1G grade, 1GV sub-grade, no upper parameter value has been determined. For this case, $V^{daf} = 38\%$ and more. Such an approach to determine V^{daf} alteration boundaries is kept for many ranks, grades, sub-grades, and classes. During development of coals classification by manifestation of their hazardous characteristics, it is desirable for this disadvantage to be eliminated. Advantage of V^{daf} parameter for its application for any purposes consists in its sufficient previous study in part of correlation relationship with other parameters. Ultimately, coals of all grades from D to T were assigned to the group of increased endogenous hazard. Coal of the same grades from D to T fell into the category of coal seams, where endogenous fires were absent. This once again indicates the absence of a direct connection between V^{daf} and M indicators with the manifestation of hazardous properties of coal seams. The values of the volatile matters yield can differ significantly for different mines due to the heterogeneous petrographic composition of the organic mass [2]. To clarify the consumer properties of coal, this requires an individual determination for each mine formation, taking into account changes in coalification indicators. The same approach is required to establish the hazardous properties of coal seams, but using a different set of classification indicators.

The problem of establishing a indicators set for predicting the hazardous properties of coal seams appeared as a result of copying without scientific substantiation of industrial classification methods for determining the stages of coal metamorphism (grades). At all stages of improving industrial classifications, the main criterion for the distribution of coals by consumer properties has been and remains to this day the yield of coke to organic matter (K). According to this indicator, 10 stages of coal metamorphic transformations were initially conventionally established. The classification diagram developed later [6] was based on the coals distribution by their sintering capacity into 4 groups. Weakly caking coals were determined by the values of V^{daf} and C_0, caking ones were classified using V^{daf} and the thickness of the plastic layer (y), weakly caking coals were grouped according to V^{daf} and tar yield (T^{daf}_{sk}), and the gradation of non-caking coal and anthracites was made according to the specific gravity (K_d) of organic matter and mechanical copra strength (P_c). In the case under consideration, different pairs of main indicators were selected to characterize different degrees of one consumer property manifestation. In addition, the oxygen content in organic matter (O_0) and the higher heat of combustion for the wet ash-free state of the organic matter (Q^{af}_s) were taken into account. Subsequently, using the values of V^{daf}, y, Q^{af}_s and maximum moisture capacity (W^{af}_{max}),the coal was divided according to their technological qualities into 10 grades (D, G, GZh, Zh, KZh, K, K2, OS, SS, T) and six stages of metamorphism. The discrepancy between the grades and the number of stages is due to the fact that the transitional grades (GZh, KZh, OS and SS) were determined simultaneously by two stages of metamorphism. After improvement, the modern industrial classification [8] divides all fossil coals using 10 indicators into eighteen grades, including brown coal and anthracite. In addition to establishing the brand identity, a gradation was made into groups, subgroups, classes, categories, types and subtypes. A total of 86 varieties of fossil coal have been identified. Correspondence to these varieties of the same number of stages of metamorphic transformations of formations has not yet been made. The solution to this problem is not a priority for establishing the consumer properties of coal. In contrast to industrial classifications, determining the conformity of individual stages of metamorphic transformations of coal seams is a primary task for improving the regulatory framework for the safe conduct of mining operations. The division into 10 stages of metamorphism of formations according to the yield of coke [6] has remained practically unchanged to date. Their number coincides with the number of originally established brands. This allows, as a first approximation,

Table 1. Information on the average composition of the Donetsk basin coals at different stages of seam metamorphism and removed fluids.

Coke yield to organic matter,% K/$\bar{K}$	Stages of metamorphism	Removed fluids,% V_k^a /$\bar{V_k^a}$	Average elemental composition of organic matter,% $\bar{C_0}/\bar{H_0}/\bar{N_0}/\bar{S_0}/\bar{O_0}$	Brand affiliation M
52-55/53.5	1	48-45/46.5	80.19/5.34/1.43/2.28/10.76	D
55-60/57.5	2	45-40/42.5	81.57/5.31/1.44/1.83/9.85	G
60-65/62.5	3	40-35/37.5	84.29/5.31/1.44/1.42/7.54	GZh
65-70/67.5	4	35-30/32.5	86.43/5.21/1.46/1.24/5.66	Zh
70-75/72.5	5	30-25/27.5	88.33/5.10/1.52/1.10/3.95	KZh
75-80/77.5	6	25-20/22.5	89.53/4.81/1.51/1.04/3.11	K
80-85/82.5	7	20-15/17.5	90.43/4.60/1.51/1.06/2.40	K2
85-90/87.5	8	15-10/12.5	91.46/4.30/1.38/1.03/1.83	OS
90-95/92.5	9	10-5/7.5	92.67/3.75/1.32/1.00/1.26	SS
95-100/97.5	10	<5/2.5	93.65/1.93/1.05/0.74/0.63	T

to compare the grades of coal with the corresponding stages of metamorphic transformations of coal seams (table 1). Developed on the analysis results basis of the currently known indicators of the coal metamorphism degree and the scientific substantiation of their possible application for characterizing the hazardous properties of coal seams.

The yield of coke to organic matter uniquely determines the removal of fluids (V_k^a) at each stage of a formation transformation. The average value of coke ($\bar{K}$) corresponds to the amount of removed fluids ($\bar{V_k^a}$), based on the condition of their total 100% content in the dry ashless organic mass of the mine formation:

$$\bar{V_k^a} = 100 - \bar{K}, \%$$

In this case $\bar{V_k^a}$, in addition to gaseous products, the composition includes coal tar, pyrogenetic moisture, crude benzene and other products of formations metamorphic transformations. Significant changes are also observed in the elemental composition of organic matter (figure 1).

According to the one-sided direction of the processes of metamorphism, with their intensification, an increase in the content of carbon ($\bar{C_0}$) and a decrease in hydrogen ($\bar{H_0}$), nitrogen ($\bar{N_0}$), sulfur ($\bar{S_0}$) and oxygen ($\bar{O_0}$) occur. The reduction of individual components in the organic mass at different stages of metamorphism occurred with different intensity. Their total amount (figure 1b) is strictly controlled by the carbon content (figure 1a), based on the ratio:

$$\sum \bar{H_0}, \bar{N_0}, \bar{S_0}, \bar{O_0} = 100 - \bar{C_0}, \%$$

Equation represents the total elemental balance of dry ashless matter at different stages of fossil coals conversion. It does not take into account the change in moisture in the original sample $\bar{W^a}$ (figure 1b), a as well as the ratio between coke $\bar{K}$ (dry residue) and fluids $\bar{V_k^a}$ removed from the layers. The moisture influence on the manifestation of the hazardous properties of coal seams is beyond doubt [13]. The fraction of fluids removed from the layers $\bar{V_k^a}$ exceeds the yield of volatiles $V^{\bar{d}af}$ per dry ashless mass.

Significant differences in the balances between the ongoing metamorphic processes in coal seams and during the thermal decomposition of coal are caused by different methods of their determination. The assignment of the thermal decomposition processes products to a dry ashless

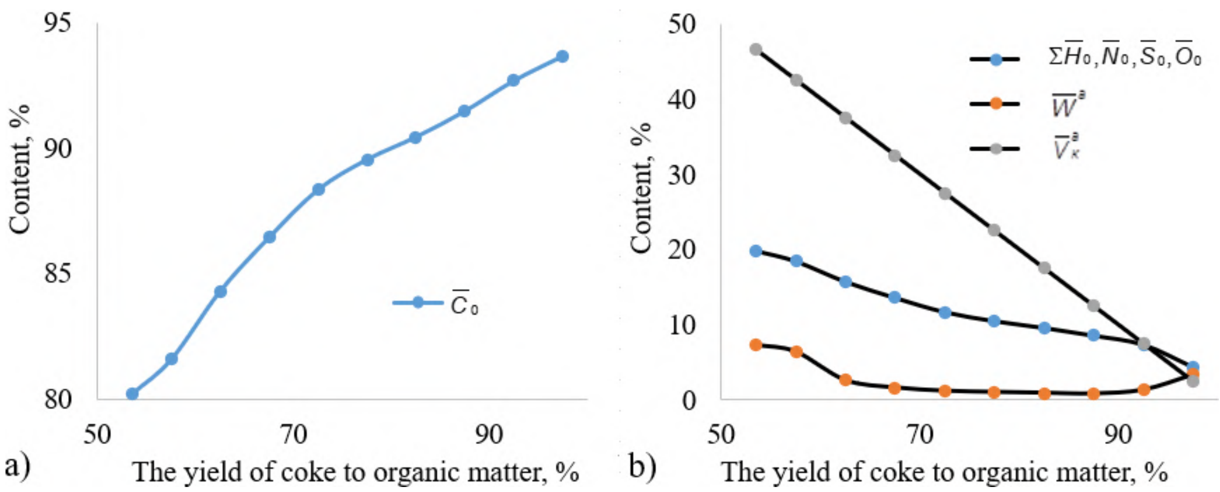

Figure 1. Dependence of the organic matter content and volatiles removal from the layers on the yield of coke to organic matter.

mass according to industrial classifications does not allow the use of their consumer properties indicators for characterizing coal seamsin natural conditions. The hazardous properties of coal seams cannot be directly determined by the yield of coke to organic matter. According to the K value, the stages of coals metamorphic transformations were initially only approximately determined. At different stages of metamorphism, the composition of organic matter, almost 100% (table 1), is determined by the sum of the components $(H_0, N_0, S_0, O_0, C_0)$.

The relationship between them in the process of metamorphic transformations does not remain constant. Only an increase in the elemental content of carbon in organic matter occurs unambiguously $\bar{C_0}$ (figure 1). Other indicators of the degree of metamorphic transformations $(\sum \bar{H_0}, \bar{N_0}, \bar{S_0}, \bar{O_0}; \bar{V_k^a}; \bar{W^a})$ vary according to different dependences. The manifestation of the hazardous properties of coal seams is largely determined by the elemental composition of organic matter. For this reason, the methodology for their prediction should be based, to a large extent, taking into account changes in the elemental composition of organic matter. Its main constituent at the stages of coal and anthracite formation is carbon. Its content increases in the range from 70 to almost 100%. When the carbon content is less than 93%, the sum of the remaining components of organic matter $(\sum \bar{H_0}, \bar{N_0}, \bar{S_0}, \bar{O_0})$ decreases according to a linear inverse proportional relationship (figure 2).

A linear inversely proportional decrease in the total of organic matter components with an increase in carbon content indicates the predominant mechanical removal of fluids at the early and middle stages of layers metamorphism and an insignificant amount of formation of new chemical compounds with the participation of carbon. At values $\bar{C_0} > 93\%$ the dependence $\sum \bar{H_0}$,$\bar{N_0}$,$\bar{S_0}$,$\bar{O_0}$ from inversely proportional to nonlinear, which indicates the possibility of the formation of new chemical compounds under the influence of elevated temperatures and pressures.

Other indicators of metamorphic transformations of formations – removal of fluids $\bar{V_k^a}$ and the content of analytical moisture $\bar{W^a}$ also depend on the carbon content in organic matter. This gives rise to the value together with the individual content of other organic matter components H_0, N_0, S_0, O_0, C_0 and moisture, to be considered the main indicators affecting the safety of mining operations. The dependence of the fluids removal $\bar{V_k^a}$ at different layer stages differs significantly from the yield of volatiles $V^{\bar{d}af}$ during the thermal decomposition of coal. The difference between and at the early and middle stages of layer transformation $(\bar{C_0} \approx 70 \div 90\%)$

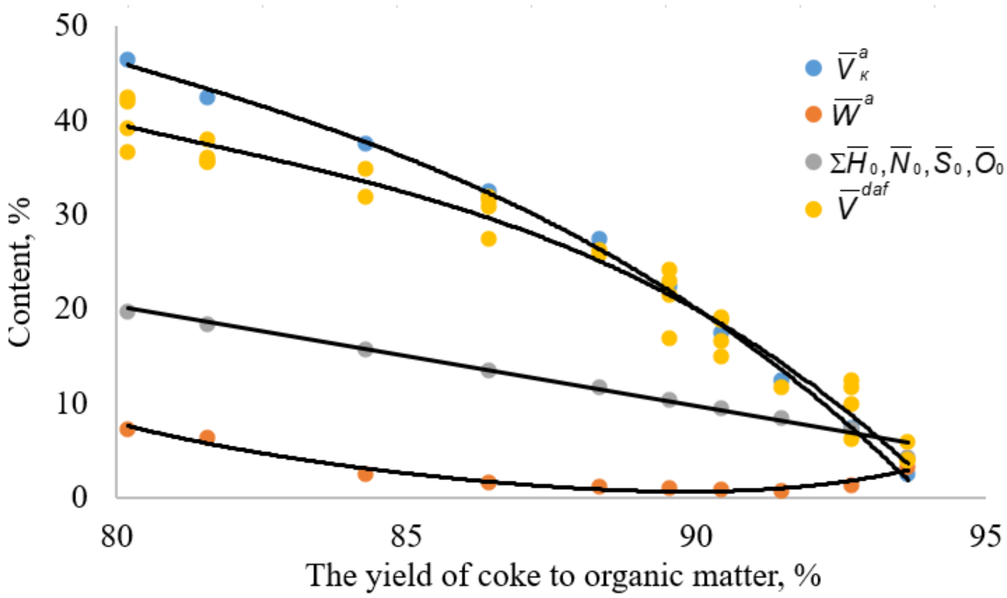

Figure 2. Dependence of the average indicators of seams metamorphism and the yield of volatile substances from organic matter due to coal thermal decomposition on the average carbon content in organic matter.

is due to the removal of moisture and coal tar from them along with gaseous products. The determination procedure V^{daf} takes into account only the total yield of gaseous products. The coincidence at values $> 90\%$ indicates the predominant removal of gaseous fluids from the layers.

The values of the indicators and are determined on the basis of the average composition of the Donets basin coals. They are in full agreement with the results of the coals analysis carried out for different deposits [3, 12, 13], which indicates the sufficient reliability of the obtained results.

It is proposed by methods for predicting the hazardous properties of each mine layer to establish individual deviations of the organic matter components and moisture from their average values for the stage of metamorphic transformations under consideration. The stage of transformation is determined by the carbon content in organic matter. A significant deviation of any organic matter component ($\bar{H}_0$,$\bar{N}_0$,$\bar{S}_0$,$\bar{O}_0$,$\bar{W}^a$) from its average values causes a redistribution of their individual content in the elemental organic matter composition. This, in turn, determines the individual characteristics of the hazardous properties manifestation of coal seams during mining operations. If necessary, an additional analysis is made for anomalous composition of mineral impurities.

3. Conclusions

The studies carried out made it possible to establish the features of the metamorphic transformations stages and their differences from the processes of coals thermal decomposition, to develop a methodology for predicting the hazardous properties of coal seamsto improve the regulatory framework. Its main provisions are based on the following principles:

- intensification of layers metamorphic transformations is associated with a one-sided increase in the carbon content in organic matter and a change in the content of other components (hydrogen, nitrogen, sulfur, oxygen, moisture);
- one of the main factors determining the manifestation of the hazardous properties of mines is the elemental composition of the original organic mass and the degree of its transformation

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during geological processes;

- metamorphic transformations of brown coal seams occurred at temperatures up to 300-325°C, stone – at a temperature of 325-500°C. Achievement of the anthracite stage corresponded to a temperature of 500-650°C;
- the final conversion cycle of the original organic matter consists in achieving the elemental carbon content close to 100% and approaching zero of the sum of the content of the remaining components;
- the temperature of coals thermal decomposition without air access (900°C) when establishing their technological properties significantly exceeds the temperature of metamorphic transformation of seams (300-650°C). This allows us to consider the products of thermal decomposition as the next stage of coal transformation, which is not related to the appearance of hazardous properties of coal seams;
- there are currently no methods of complete demineralization of the coal sample. Obtaining an accurate value for the yield of volatile substances per dry ashless organic mass leads to an overestimation of this indicator. The error increases with the increase in the proportion of the mineral component. When the carbon content is less than 93%, the sum of the remaining components of organic matter ($\sum \bar{H}_0,\bar{N}_0,\bar{S}_0,\bar{O}_0$) decreases according to a linear inverse proportional relationship;
- the method for determining the yield of volatile substances on a dry ash-free mass when establishing technological properties does not reflect the state of coal seams in natural conditions;
- the method for determining the yield of volatile substances on a dry ash-free mass when establishing technological properties does not reflect the state of coal seams in natural conditions;
- the basic principles of the methodology for predicting the hazardous properties of mines are proposed to be developed based on the deviation of the content of the organic matter main components, including moisture and sulfur, from their average indicators.

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An integrated approach to forecasting and managing emergency situations in the working faces of coal mines: a set of technical, organizational and measures to ensure occupational safety with subsequent assessment of potential consequences

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An integrated approach to forecasting and managing emergency situations in the working faces of coal mines: a set of technical, organizational and measures to ensure occupational safety with subsequent assessment of potential consequences

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Abstract. The need for worker safety in the coal mining industry is critical because workers in this industry are exposed to a number of hazards and risks. Accidents occurring in the technogenic sphere of the coal industry cause significant damage to the state economy. Loss of production, repair and restoration of infrastructure, compensation to victims, damage to the environment require significant financial outlays. Therefore, it is important to take all necessary measures to prevent accidents and minimize their consequences. The purpose of the work is to identify the zones of manifestation of hazards and forecasting the risks of emergencies, as well as to develop a set of technical and organizational measures to prevent accidents and incidents during production work. The importance of the study lies in the development of recommendations for identifying the main risk factors in coal mines cleaning faces, the creation of a set of technical and organizational measures to quantify the risk of emergencies, as well as improving the level of safety of the main working processes in planning safe mining operations. Ensuring safety of coal industry workers is an integral part of successful and efficient operation of this industry.

1. Introduction

Accidents and industrial injuries that occur in the technogenic sphere of the coal industry are a source of enormous damage to society and the state as a whole. Development and implementation of measures to ensure efficiency the functioning of systems for preventing and eliminating accidents in longwalls seems to be difficult in conditions of insufficient knowledge of the patterns of man-made hazards, the occurrence of emergency situations and the causes leading to them. This is especially noticeable in the absence of a systematic analysis of risk factors and effective methods for predicting the level of safety at such stages as design and organization of production [1]. The development of risk assessment methods is the most important condition for forecasting man-made hazards, the occurrence of emergency situations, their consequences, and damage assessment. This will allow us to identify effective measures to prevent accidents and injuries at the planning stage of mining operations. To reduce the likelihood of man-made emergency situations at coal mining enterprises, taking into account the requirements of legislation in the field of labor protection, it is necessary to develop and implement a set of organizational and technical measures [2]. They should be aimed at predicting and assessing risk factors, improving the occupational safety and mining safety management system, taking into account the concept of acceptable risk, and revealing the basic patterns of formation of the preconditions for negative events depending on the technical level of production and mining and geological conditions. 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, 2].

Increasing the level of safety of mining operations in the working faces of coal mines is also associated with improving methods for predicting places of possible emergency situations based on the analysis of geomechanical and gas-dynamic phenomena, such as rock bursts, sudden outbursts of coal and gas, increased rock pressure, roof collapse, caused by the morphology of deposits coal [3]. Therefore, at present, in order to maintain the required level of labor protection and industrial safety, scientific research on the development of a set of technical and organizational measures to predict emergency situations in the working faces of coal mines and assess their consequences can objectively be qualified as relevant.

The purpose of the work is to establish the influence of a complex of mining-geological and technological factors on the formation of the preconditions for emergency situations to identify dangerous zones of hazard manifestations and predict the risks of emergency situations and to develop a set of technical and organizational measures to prevent accidents and injuries during mining operations [4]. This consists of implementing a systematic approach to object-oriented assessment of the risk of emergency situations during cleaning operations in coal mines, taking into account the geodynamic manifestations of rock pressure to predict high-risk zones. The main provisions of which are:

- the methodology for assessing and predicting identification of man-made hazards, risks of occurrence and dynamics of emergency situations, and their consequences is based on a comprehensive accounting of the ranks of risk factors for the conditions of a particular mine;
- ranking of the main risk factors influencing the likelihood of emergency situations is based on the methodological principles of retrospective analysis of the dynamics and consequences of man-made hazards in the working faces of coal mines [5];
- reliable forecasting and effective monitoring of man-made emergency situations, on the basis of which effective protective measures are developed in dangerous zones of manifestations of geomechanical processes, is ensured by implementing the electromechanical analogy method for quickly determining the location of dangerous zones of the coal-bearing massif and assessing their values [6];
- the use of the electromechanical analogy method based on an algorithm for operational prediction of the location of emergency zones allows us to objectify the opology of the workings network of the excavation site and the direction of mining its reserves, taking into account the geomechanical factor.

To date, the Ukrainian coal industry has not solved the problem of predicting the location of man-made emergency situations in the working faces of coal mines. the problem, a significant reduction in the level of occupational morbidity of workers at coal enterprises, is an urgent and priority task [7, 8]. Existing comprehensive assessments of the hazard level require clarification and additional research into mining operations with various equipment options.

In this regard, the following tasks were set and solved:

- analysis and evaluation of the main patterns, reasons for the manifestation of hazardous factors in the working faces of coal mines;
- ranking of the main risk factors that shape the accident rate and industrial injuries in coal mines;
- research of existing methods necessary for the development of measures for operational forecasting and monitoring of safe cleaning work in coal mines;
- development of an algorithm for electromechanical modeling methods for determining and assessing the values of the horizontal components of the stressed part of the coal massif and their trajectories;
- development of methods for assessing and forecasting man-made hazards, risks of occurrence and dynamics of emergency situations, their consequences, and possible damage.

2. Results and discussion

The study and processing of an array of statistical data on the manifestation of man-made hazards revealed the main groups of risk factors influencing the occurrence of emergency situations [9,10]. The ranking of the main risk factors was carried out on the basis of determining the specific gravity of the groups (f) as the ratio of each of them to the total number of manifestations of hazards over a given period of time. As a result, several thousand cases of industrial risk were analyzed, more than thirty enterprises and organizations were studied. The spread of basic data on the share of risk factors (standard deviation) for various geological and mining conditions did not exceed 10% (table 1, figure 1). Based on the results of the study of the main risk factors, it was possible to find out that the greatest number of manifestations of man-made hazards are associated with gas-dynamic, hydrodynamic and, mainly, geodynamic phenomena. Now in this area there is a significant lag in the development of new effective measures for the operational forecasting of emergency situations associated with the uncontrolled growth of the stressed state of the mountain range. An assessment of the magnitudes and directions of action of deformations and stresses in the presence of blockiness of the massif can be performed using methods of mathematical modeling of the stressed state of a coal seam, the distinctive feature of which is the efficiency and clarity of the solution process.

Analysis of the modeling results indicates that the manifestation of geodynamic phenomena in the marginal parts of the mountain range associated with the stressed state of the coal seam depends mainly on the tectonics of the deposit. It was found that the system of tectonic faults makes the most significant contribution to the nature of the stress state of flat and inclined coal seams [11]. Therefore, one should expect dynamic phenomena of rock pressure in the immediate vicinity of the fault plane at the moment when the maximum stress state of the massif is reached. During the movement of cleaning work in the roof of the fault plane, the stress state of both the edge of the formation and the fault plane itself is summed up. Mathematical modeling methods have been known for quite a long time and not only in Ukraine, its application has been carried out for the conditions of many ore deposits and is described in methodological manuals. In mines in England and Germany, modeling methods are integrated into management systems labor protection [12]. The use of this method in domestic mines to predict the risk of accidents and injuries would improve the level of industrial safety and labor protection. Therefore, the result of further research based on the integration of electrographic modeling into the system of mine services was the development of an algorithm for operational forecasting of the location of man-made emergency situations (figure 2).

This algorithm includes determining the location and assessing the values of the horizontal components of tectonic stresses, their trajectories for the conditions of the mining site of a mine based on electrographic modeling [13]. The algorithm also includes a retrospective analysis of

Table 1. Grouping the main risk indicators.

Group	Risk	Risk factors	f, units
Group 1	Natural action	Tectonics, blockiness, disturbances, depth, gas hazard, impact hazard, emissions hazard, explosion hazard, dust pollution, fire hazard, hydrohazard.	0.30
Group 2	Monitoring array and lava (availability)	Numerical sediment recording; application of the optical-imaging method of georadar location; seismic tomography; reservoir mapping; Internet; phone; presence of geo-, hydro-, micro-, vibraphones; communication-information system	0.23
Group 3	Equipment	Technical readiness coefficient; firm; operating time; wear; computer control of a mine or site; degassing	0.17
Group 4	Constructive factors	Visors; aprons; screw; protection from gas, rock bursts, sudden outbursts of coal and gas, collapses, flashes, overturns; ergonomics; telecontrol, remote, infrared control.	0,11
Group 5	Technological factors	Rear sights; roof management; speed; lava length; drilling; meeting angles; direction of faces; passport.	0.09
Group 6	Installation and testing of equipment	Quality of installation and testing; flaw detection; inspection; non-destructive testing examination; certification.	0.06
Group 7	Other factors	Personnel qualification level; physical and psychological state; certification; protective exchanges; installation control; age; occupational diseases; organizational factors.	0.04
Σf			1.00

man-made hazards and risk factors at a given facility, and determination of their specific weights. The final stage is an assessment and forecast of the risks of emergency situations and damage from them. The result of the research is the development of measures for the safe conduct of cleaning work, the main task which choose the direction of lava movement depending on the values of the horizontal components of tectonic stresses and their trajectories.

In professional risk assessments, risk typically combines the likelihood of an event occurring with the impact it would produce, as well as the circumstances surrounding the occurrence of that event.

Assessment and forecast of risks of emergency situations and damage from them as the final stage of the algorithm for operational forecasting of the location of emergency situations is carried out using a specially developed methodology.

$$\lambda = \sum_{i=1}^{7} fN, \tag{1}$$

where λ is the average expected number of accidents (frequency, risk), accidents/million tons per year; f is probability of risk factor occurrence (specific gravity) according to mine data (figure 1,

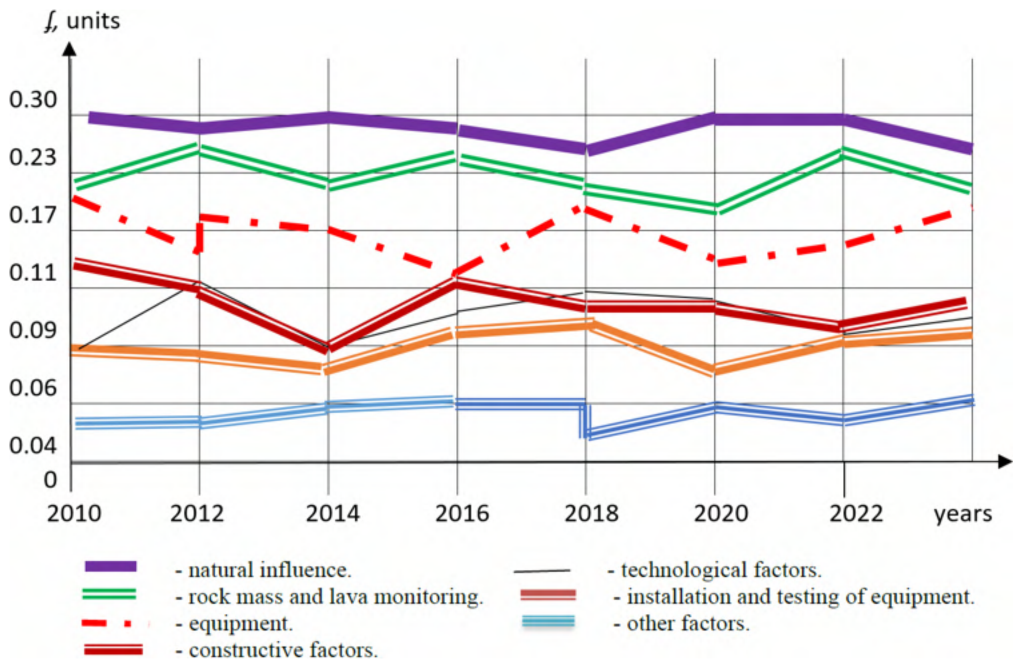

Figure 1. Dynamics of man-made hazards in mine working faces.

table 1), units; N is accident statistics, number of pieces/million tons per year.

When calculating the average expected number of accidents data should be used retrospective analysis of man-made hazards and accident rates injuries at this mine. Further, for clarity, this method presents results of calculations based on data from the coal industry as a whole (table 2).

Table 2. Average expected number of accidents during an emergency.

Emergency situations from an accident	Quantity, N pieces/million tons year	Group	Factor share, f, units	Frequency, λ accidents/million tons per year
1 Violation of the pelegas regime, spinning, heaving	350	1	0.3	35
2 Blowouts	30	2	0.2	6.0
3 Collapse	10	3	0.2	2.0
4 Rock bumps	5	1	0.3	1.5
5 Explosions of methane, dust	2	1	0.3	0.6
6 Rock pressure, disturbances, flooding, pulp breakthroughs	8	5	0.1	0.8
7 Fires	1	1	0.3	0.3
Sum, Σ				46.2

Calculation of the expected risk of technical downtime accidents were carried out according to the formula obtained from formula 1.

$$R_d = \lambda \sum_{k=1}^{2} \sum_{i=1}^{7} f_{1k} T_{1k}, \tag{2}$$

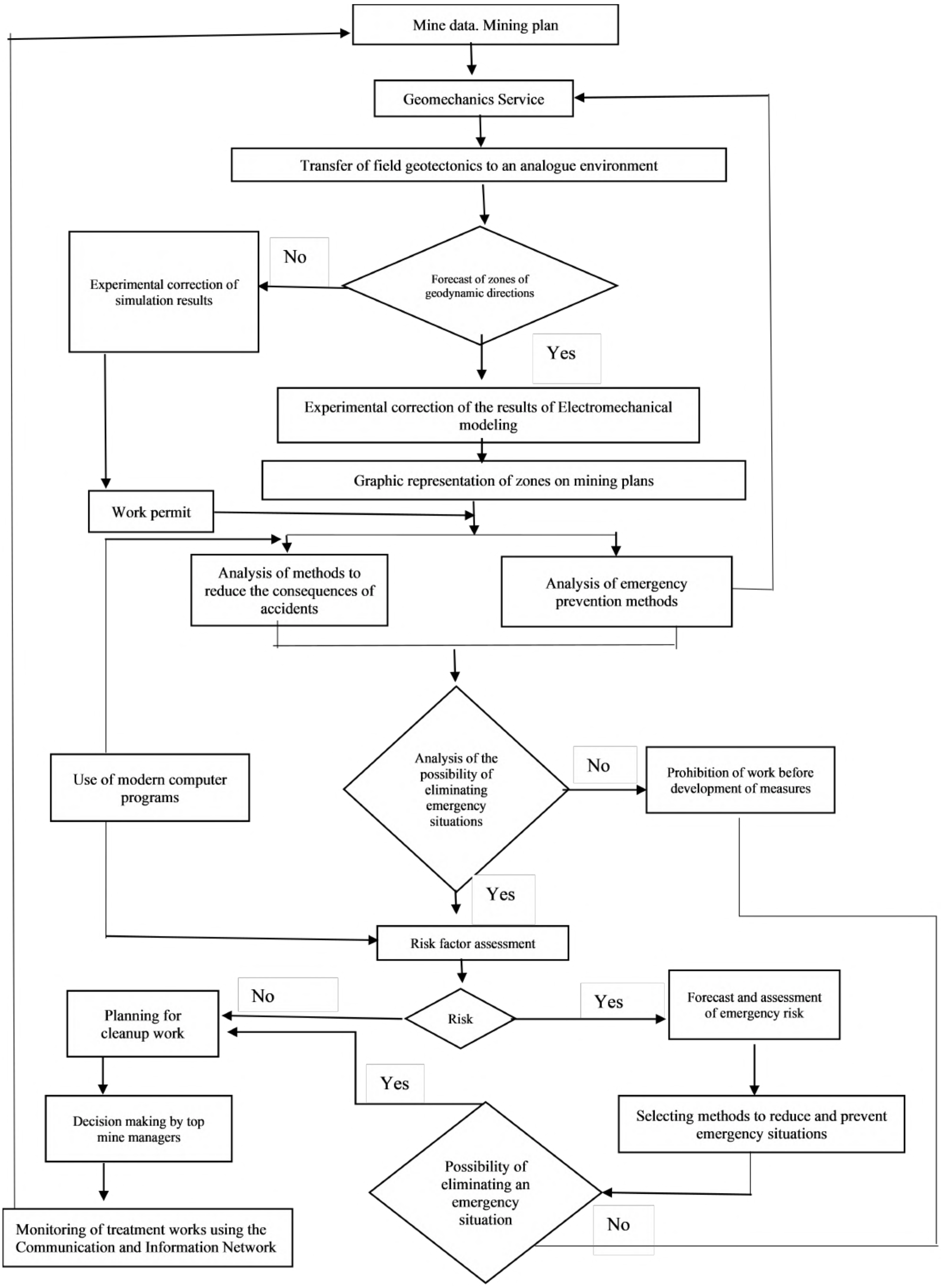

Figure 2. Scheme of the algorithm for operational forecasting of the location of emergency situations.

where R_d is the expected risk of downtime, av./million tons per year; λ (frequency) or accident risk for a given mine (formula 1); f_{1k} is share of downtime or external environmental factors, as well as from stoppages during rescue operations, units; T_{1k} is stop time during rescue operations, days.

The algorithm for calculating accidents during downtime of a mechanized longwall in coal mines is presented in figure 3.

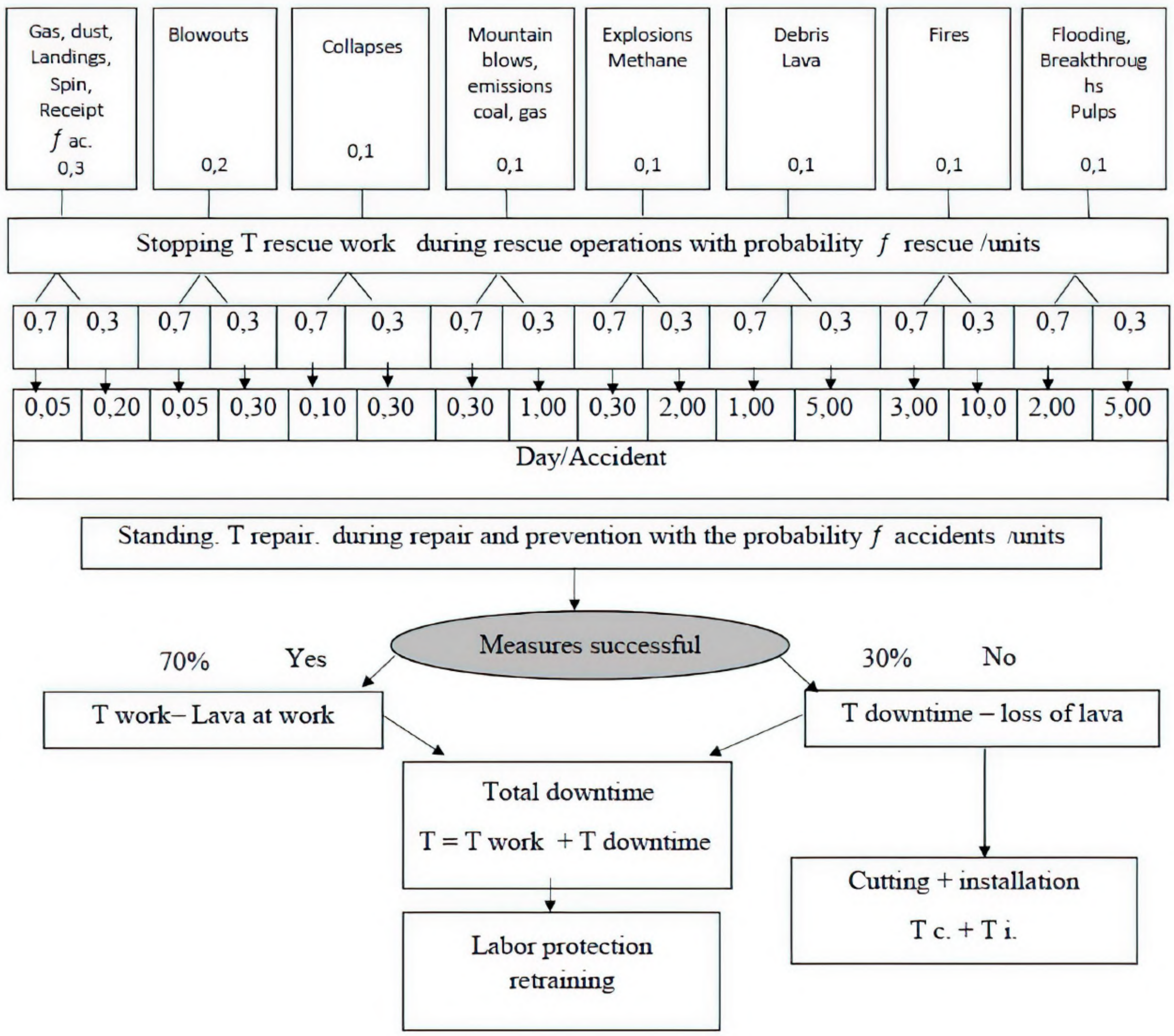

Figure 3. Downtime during emergencies with probability f accidents/units; T rescue work – time during rescue operations, day; T repair – time for repair and prevention, days; T work – operating time of the lava, days; T downtime – lava downtime, days; $Tc.$, $Ti.$ – time of cutting and installation of lava, days; T – total downtime, days.

By transforming formula 1, we calculate the risk of death injuries during coal seam mining man/longwall year).

$$R_f = \sum_{i=1}^{7} fN_s, \tag{3}$$

where R_f – risk of fatal injuries, person/year; f – share occurrence of a negative event, units;

N_s – statistics of fatal injuries for a given mine, person/million tons per year.

Safety conditions for working in the longwall

$$R_a \leqslant R_f, \tag{4}$$

where R_a and R_f are, respectively, the actual and permissible risk levels of emergency situations in the event of accidents.

Damage from the implementation of negative events (calculated damage)

$$D_c = \sum R_f, \tag{5}$$

where is D_c the damage caused to the mine by fatally injured people, c.u./person victims; R_f – the risk of fatally injured, person/lava per year.

The level of risk of an accident at the mining site, taking into account the downtime of the longwall from emergency situations, based on retrospective analysis of accident rates at coal mines is

$$R_a = \lambda T, \tag{6}$$

where R_a – risk level of longwall downtime due to accidents, day/longwall year; λ – average expected number of accidents (frequency), accidents/million tons per year; T – longwall downtime due to accidents, days/year.

Research has made it possible to create a cost chart for monitoring and measures to reduce risk factors in working faces of coal mines (figure 4).

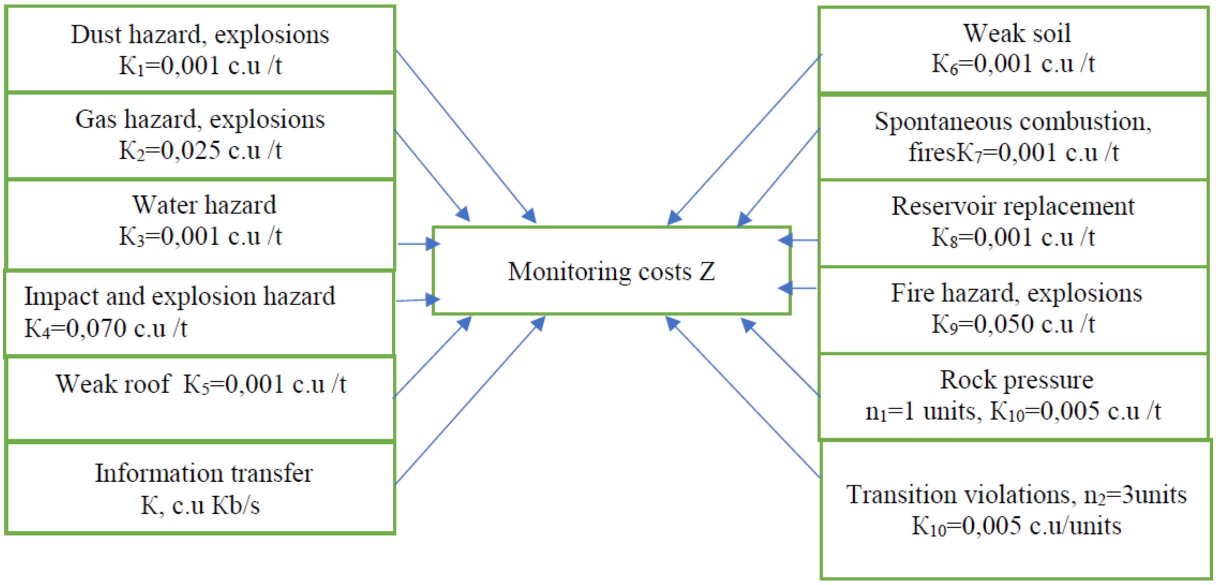

Figure 4. Scheme of costs for monitoring and measures to reduce risk factors coefficients $K_1 - K_9$ specific costs per ton of coal, $K_{10} - K_{11}$ specific costs to overcome negative factors, c.u/units.

Conditions for the economic efficiency of the project and the costs of monitoring and activities in the longwall for the conditions of this mine

$$Z = (K_1 + ... + K_9 + K_{10}n_1 + K_{11}n_2)P, \tag{7}$$

where Z is the cost of monitoring and safe measures, c.u.; $K_1 - -K_9$ specific cost coefficients per ton of coal, c.u./t; $K_{10} - -K_{11}$ specific cost coefficients to overcome negative factors, c.u./pcs.; $n_1 - -n_2$ – units of risk factors; P – load on lava per year.

Preventing man-made emergencies in the working faces of coal mines, increasing production efficiency, safe mining operations and, as a consequence, minimizing occupational injuries depend on the development, improvement and implementation of integrated occupational safety management systems [14, 15]. In order to systematically achieve a high level and constantly use the potential of modernization, the future implementation of the concept of the occupational safety and health management system, it is necessary to use the developed algorithm for operational forecasting of the location of emergency situations. In order to more effectively manage hazardous mine processes, significantly reduce occupational injuries and improve occupational safety, as the experience of the leading countries of the world shows, it is necessary to involve independent contracting commercial organizations that have licenses to carry out specialized mining operations, such as ventilation, degassing, control of dust and gas conditions, hydro, gas, geodynamic phenomena, excavation and cleaning work [16, 17]. A radical measure to prevent man-made emergency situations is the choice by the geomechanics service of the direction of movement of cleaning work relative to the trajectories of the horizontal components of tectonic stresses based on a forecasting algorithm emergency situations. Thus, using the developed algorithm for operational forecasting, data from mathematical modeling of the mining and geological conditions of the mine, as well as the specific weights of risk factors, it is possible to forecast, monitor and assess man-made hazards, risks of emergency situations, their dynamics and consequences, as well as assess damage from them.

3. Conclusions

The main conclusions are as follows:

1. Conducted studies of natural and man-made hazards, basic patterns, reasons for the manifestation of hazardous factors in the working faces of coal mines made it possible to identify seven groups of risk factors, such as natural exposure, rock mass and longwall monitoring; equipment, design factors; technological factors, installation and testing of equipment, other factors.
2. Groups of risk factors are ranked in accordance with the specific weight of influence on the occurrence of man-made emergency situations.
3. An algorithm has been developed for the mine service to quickly predict the location of man-made emergency situations, which includes the method of electromechanical analogy and a methodology for predicting and assessing the risks of accidents in the working faces of coal mines.
4. A methodology has been developed for assessing and forecasting the risks of emergency situations, their dynamics and consequences, technical downtime, fatal injuries, loss of a mechanized complex, damage from longwall downtime in an environmental accident.
5. Based on the methodology for assessing and forecasting the risks of emergency situations, quantitative values of possible damage from the manifestation of man-made hazards during underground coal mining were obtained.
6. A set of organizational measures and recommendations has been developed to ensure the safe conduct of underground coal mining, based on the results of forecasting and monitoring of geodynamic manifestations processes that provide a reasonable choice of the direction of movement of preparatory and cleaning work, taking into account the values and vectors of the horizontal components of the stressed part of the surrounding massif.

Based on the research, the problem of developing a set of technical and organizational measures for forecasting man-made hazards, risks of occurrence and dynamics of emergency

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situations, their consequences and assessing damage in the working faces of coal mines, which is of significant importance for the coal industry, was solved.

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Application of prefabricated retaining walls with increased shear resistance to ensure tailings dam stability

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Application of prefabricated retaining walls with increased shear resistance to ensure tailings dam stability

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Abstract. Tailings ponds and sludge storage facilities do not currently meet modern standards that regulate the requirements for operational safety, reliability, stability and durability. The research considers new constructive solutions for retaining walls with increased shear resistance due to passive soil resistance. Schemes and designs of tailings dams are analyzed. A comparative analysis is carried out using recommended methods to determine the safety factor for the design slip curves. The regularities of the influence of multilayer nonlinearly deformed backfill and external loads are established and new principles for determining the horizontal pressure on the retaining wall are formulated. The development of new design solutions for retaining walls and calculation methods for determining the lateral pressure of multilayer backfill is an urgent scientific task. Consideration of the influence of a multilayer nonlinearly deformed massif under external loading allows formulating new principles for determining the horizontal pressure on the retaining wall.

1. Introduction

Accumulation of a significant amount of industrial waste is associated with the development of the mining and metallurgical industry in Kryvyi Rih. The volumes and areas of production sludge and concentration tailings have grown considerably over the long term of operation. This negatively affects the state of technological and environmental safety and worsens the environmental situation in the adjacent areas [1–5].

Tailings ponds and sludge storage facilities do not currently meet modern standards that regulate the requirements for operational safety, reliability, stability and durability as they were designed in the last century [6, 7].

Application of retaining walls is proposed to prevent or avoid the negative engineering conditions of dams and embankments.

In the practice of designing retaining walls, no engineering method has been developed that takes into account the multilayer nature of the foundation in the presence of surface loads. The existing methods of H.K. Klein and other authors cannot be used because each layer of heterogeneous backfill, when taking into account the weight of the soil, has its own most unfavourable slope angle of the sliding planes, and the patterns of pressure distribution in the massif caused by different types of payloads have not yet been found. Therefore, even the simplest superposition method, which allows summarizing the pressure caused by the soil and the loads on the surface, remains technically unfeasible for multilayer soil.

Current engineering practice assumes that loads outside the traditional prism of failure do not affect the retaining wall, but this is not true and can lead to accidents.

The development of new design solutions for retaining walls and calculation methods for determining the lateral pressure of multilayer backfill is an urgent scientific task.

2. Research objectives

The aim of the research is to ensure the stability of tailings dams by using the proposed prefabricated retaining walls with increased shear resistance during the multilayer backfill build-up and operation of the structure.

To achieve this, the following tasks should be solved:

- to conduct an analytical review of the schemes and designs of tailings dams;
- to conduct a comparative analysis using the recommended methods to determine the safety factor for the calculated sliding curves;
- to develop a new design of the retaining wall to ensure the stability of the enclosing dams;
- to formulate new principles for determining the horizontal pressure on the retaining wall, considering the multilayer backfill and the load on the surface.

3. Results

In recent years, significant experience has been gained in the operation of storage facilities and the construction of dams and embankments made of waste and overburden.

Any type of storage capacity, except for pit and basin ones, requires the construction of enclosing dams or embankments that are washed from waste materials or filled with overburden or local soils. Depending on the technical conditions, enclosing dams or embankments can be built to their full height at once or in stages.

All existing storage facilities are divided into two types depending on the type of structures:

- dammed (filling) facilities, in which enclosing structures are erected at once to the full height or in stages;
- gradual construction storage facilities, in which a primary dam of low height is first constructed to arrange backwash, and then the storage facility is increased in height by gradually constructing secondary dams;
- damless facilities, which exclude the construction of both the embankment and the primary dam.

Depending on the terrain, the following types of storage facilities are distinguished:

- ravine dams located in ravines or gullies blocked by a dam;
- plain facilities arranged on flat ground and dammed around the entire perimeter. The operational advantage of a plain storage facility is that there is no need to discharge natural runoff and build expensive spillway structures for this purpose;
- ravine and plain facilities built on plains crossed by ravines, which are blocked by a dam, and the plain is dammed;
- floodplain facilities located on river floodplains and dammed on two or three sides, depending on the terrain;
- slope dams arranged in areas and enclosed by dams on three sides and the slope itself on the fourth;

- pit storage facilities located in dead pits, and waste can be stored without building a dam;
- basin storage facilities located in basins, where waste can be stored without a dam or a low-height dam is required.

The type of enclosing dams for the storage facility is determined depending on the availability of certain soils in the immediate construction area, the construction method, engineering, geological and hydrological conditions of dam foundations, and the capacity of the concentration plant at the mining and concentration works.

The same soils can be used to construct enclosing dams as for the construction of water retention dams and embankments, as well as waste discharged by concentration plants.

There are two ways to fill a storage facility: from the dam or the embankment to the banks and from the bank to the dam or embankment, and in the case of a plain storage facility, the dam is filled by pools. Three methods of waste inwash into in dams and embankments are recommended – trestle, zenithal and trestleless.

To construct dams and embankments, overburden and waste from concentration plants, as well as various local construction materials should be used as much as possible, specifically sand, clay soils, crushed stone, gravel, stone, etc. Soils for dam construction should meet the requirements of the standard for the design of dams made of soil materials [8].

The Mining and Concentration Plant ArcelorMittal Kryvyi Rih is an operating iron ore mining and concentration facility located in the southern part of Kryvyi Rih.

Tailings are stored alternately in Obiednane and Myroliubivka tailings ponds, which are located to the south and southeast of the central industrial site, respectively.

The operation of Myroliubivka tailings pond with a build-up layer up to the level of the 135 m and above is distinguished by an alternating block system of construction and pool washing.

First of all, the cells of the southern block (№ 6, 7-8, 9-10, and 11) are built and washed out. The northern block includes pools 1-2, 3-4, and 5. These pools are built and washed out in the second turn, and the duration of the construction of the northern block of pools is determined by the time of washing out the southern block of pools.

The Additional Compartment pool is also washed out, but its washing out period does not depend on the washing out of other blocks.

The main focus of the inspection was on the most hazardous area of the tailings pond, namely the area between S38 and S41. It required reconstruction as a result of lost stability, negligent operation and increased moisture of soils.

The design of the general tailings dam is a combined one, consisting of embanked secondary belt dams and an "washed in retaining prism" made of tailings.

The Myrolyubivka tailings pond is classified as a capital class 1 facility in terms of its capacity, overall height and degree of responsibility.

Structurally, Myroliubivka tailings facility currently consists of a primary loam dam from the crest level of 102.5 m and secondary dams are being built up at 108.5 m, 115.0 m, 120.0 m, 125.0 m, 130.0 m and 135.0 m levels. The entire perimeter of the tailings pond was previously filled with downstream surcharge: for the most part the tailing pond up to the level of 103.0 m, in the vicinity of spillway 3 – up to the level of 111.0 m.

The primary dam is constructed of loam with a retaining prism and rock overburden support. At 108.5m, 115.0 m and 120.0 m, the dams are structurally a rock prism with a tailings face. Modern man-made (rock-fill and hydraulic) formations, namely waste dumps, raise of dams, roads, sludge in tailings ponds, etc. play a significant role in the geological structure of the area. The thickness of these formations is often measured in tens of meters.

Myroliubivka tailings pond is located on Velyka Krokva gully, its slopes and adjacent areas. Velyka Krokva gully flows into Hrushevata gully.

The area around tailings ponds is built up with technological facilities and communications. Temporary man-made (rock-fill and hydraulic) formations, such as waste dumps, walls of embankments and dams, roads, sludge in tailings ponds, etc., play a significant role in the geological structure of the area. These formations are often tens of meters high.

Beneath the man-made formations in the tailings pond area under investigation are Quaternary accumulations represented by alluvial-deluvial loams, less often clays (containing organic matter), a loess-like thickness of yellow-brown and pale sandy loams, two levels of dark brown (slightly humus), red-brown loams and clays in the gullies.

The thickness of Quaternary accumulations is highly variable and reaches 20.0-23.0 m in some places. These formations are underlain by Neogene sediments of the Pontic and Sarmatian levels. Below are the Paleogene deposits, which are based on weathered crystalline rocks of the Paleozoic-Cenozoic period.

The depth of groundwaters and Quaternary sediments occurence varies widely from 0.5-1.0 m to 10-15 m. In the tailings ponds, these groundwaters are of a pressure nature. In some places, the pressure reaches tens of meters.

The waters are highly mineralized and hard, ranging from slightly aggressive to highly aggressive towards concrete.

To control the quality of the washed in tailings, the Geotechnical Control Service (GCS) took 185 samples in 23 boreholes (figure 1) on the beaches at the dike at the 140.0 m level. The monitoring time of the control and measuring equipment (CME):

- at the dam crest elevation of 140 m, 12 cycles were performed between January and December;
- at the dam crest elevation of 135 m, 1 cycle was conducted in August;
- at the 130-meter crest elevation ("Additional Compartment"), 7 cycles were conducted between January and August;
- at the 130-meter dam crest elevation, 1 cycle was conducted in September;
- at the 125-meter dam crest elevation, 1 cycle was conducted in October;
- at the 120-meter crest elevation, 1 cycle was conducted in October;
- at the 115-meter crest elevation, 1 cycle was conducted in October.

The laboratory studies determine granulometric composition of tailings.

Based on the results of CME instrumental inspections and a comparison with the previous year's results, we can conclude that there is a uniform increase in subsidence. This is due to intensive beach erosion and active construction of 140.0 m dikes.

Along the perimeter of the tailings pond, 14 CME dam site are installed on the dike from the at the crest level of 140.0 m, and 6 CME sites – in the area of the Additional Compartment at 130.0 m. Based on the results of the measurements, graphs of subsidence are built (figure 2, figure 3, figure 4, figure 5).

To monitor the depression curve, water levels are measured quarterly in piezometers (figure 6) installed on the dams at 115.0 m, 120.0 m, 125.0 m, 130.0 m and 135.0 m crest levels.

A system of drainage devices is installed to improve the reliability of the dike operation to reduce the level of the depression curve, prevent its release onto the downstream slopes and avoid pollution of surface and groundwater.

Calculations aim to assess the tailings pond condition, ensure regulatory stability during the increase of the enclosing dams to the 140.0 m level of the tailings pond and propose additional measures to ensure the required reliability during operation.

The reliability of a storage facility is understood as a complex property that consists in its ability to perform the functions of a waste storage tank under specified operational, structural, and environmental safety indicators during the estimated period of time.

Strength and stability of modern hydraulic facilities are assessed by the limit state method, according to which all the initial design values, which are random in nature, are represented by

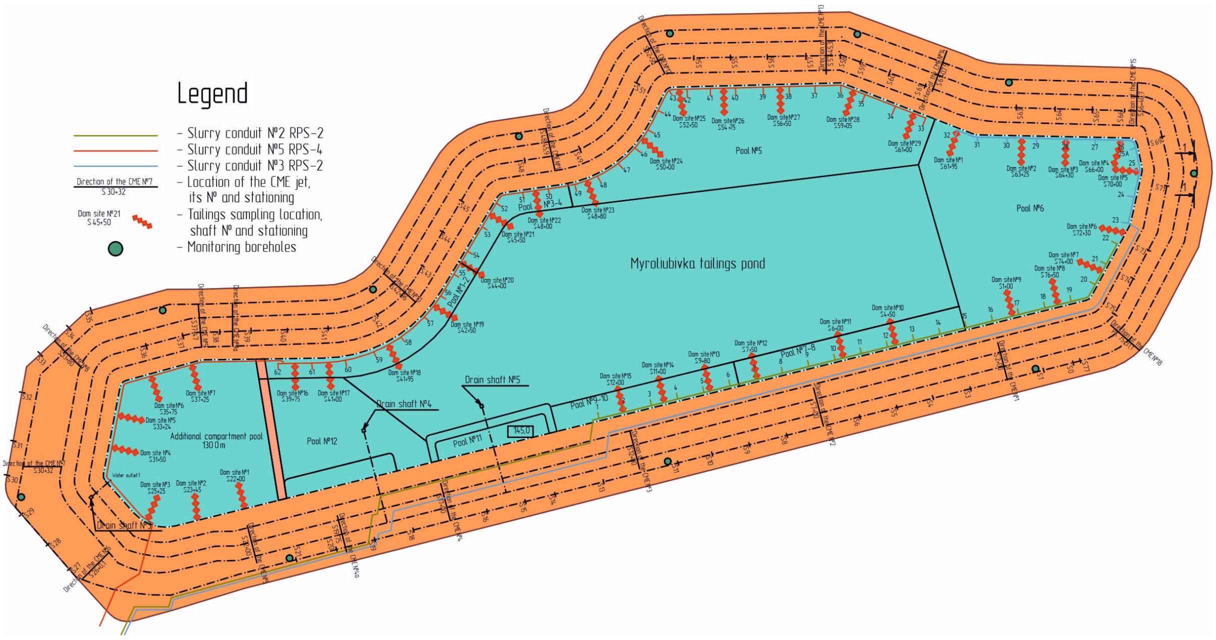

Figure 1. Tailings sampling plan for Myroliubivka tailings storage facility.

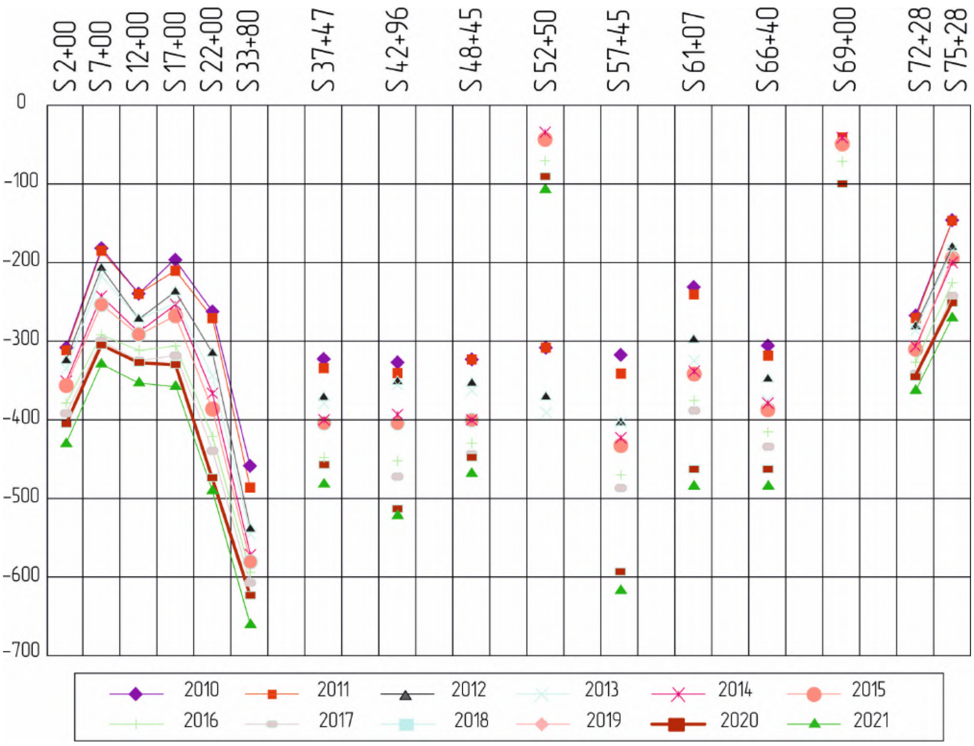

Figure 2. Subsidence diagram CME by the 120 m dike overflow levels.

some deterministic values, and the impact of this variability on structure reliability is taken into account by relevant coefficients regulated by the standards.

In the case of storage facilities, it is very difficult to consider all the randomness and uncertainties using deterministic coefficients.

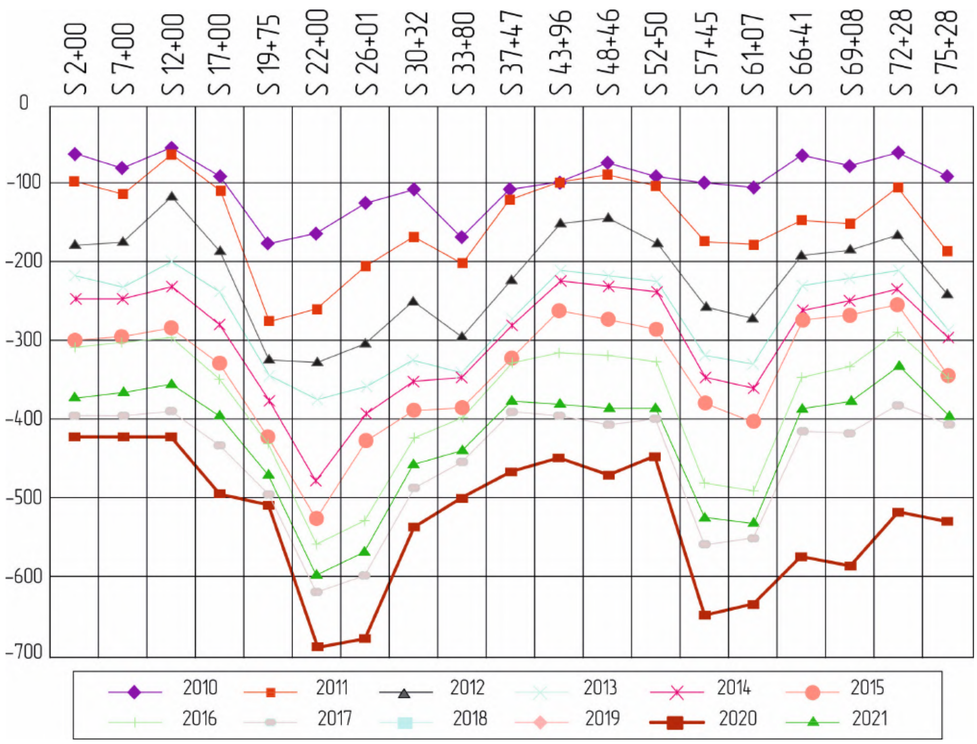

Figure 3. Subsidence diagram CME by the 125 m dike overflow levels.

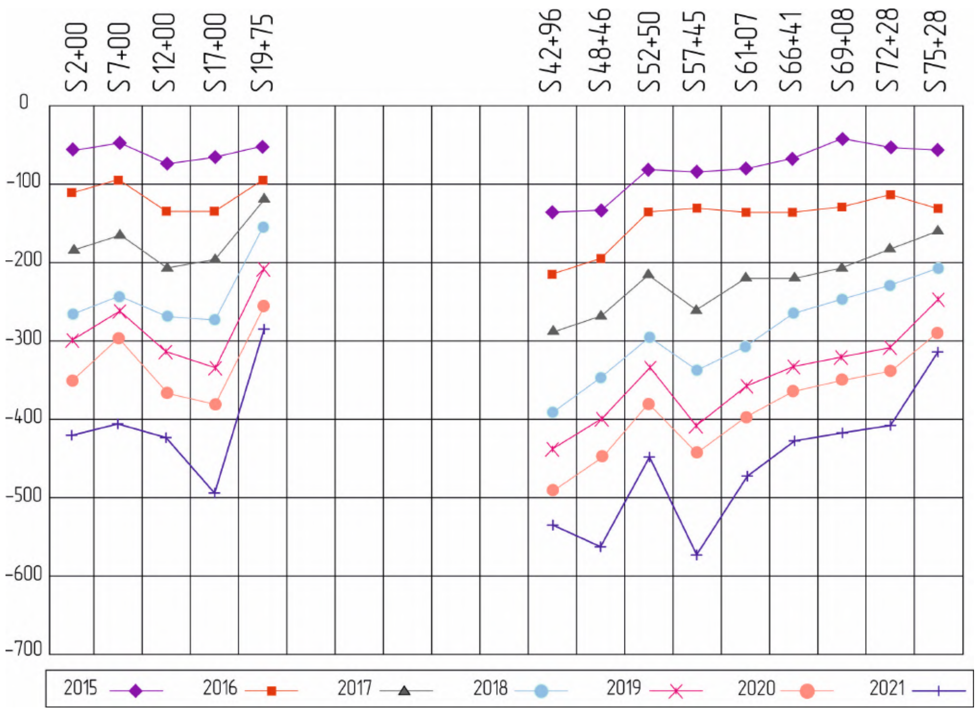

Figure 4. Subsidence diagram CME by the 130 m dike overflow levels.

As a rule, pressure structures of storage facilities are embankments of a complex layered structure, the soils and materials of which are characterised by significant variability of

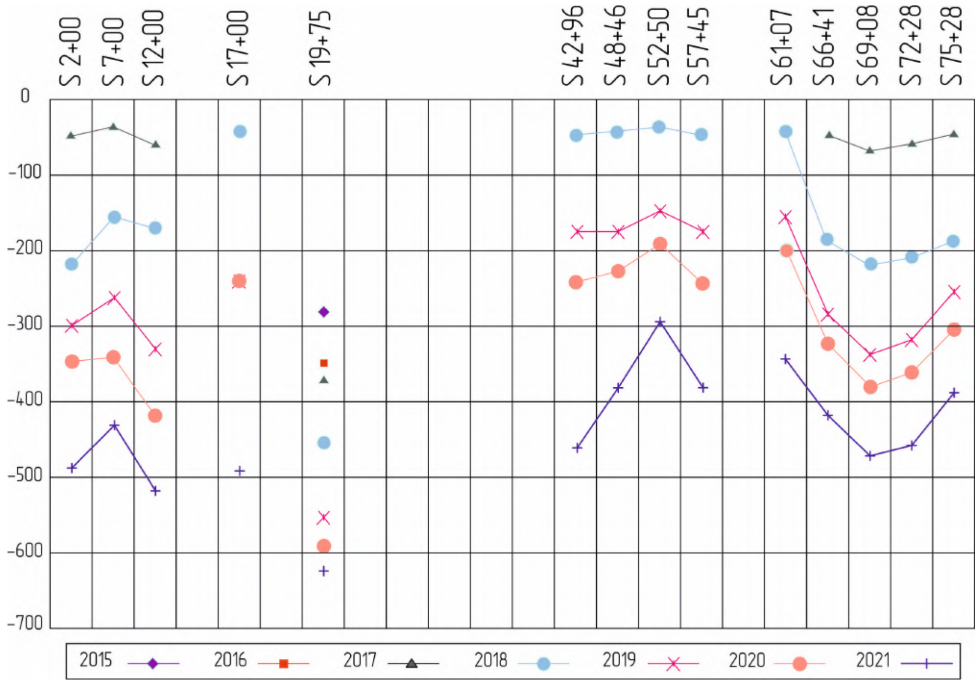

Figure 5. Subsidence diagram CME by the 135 m dike overflow levels.

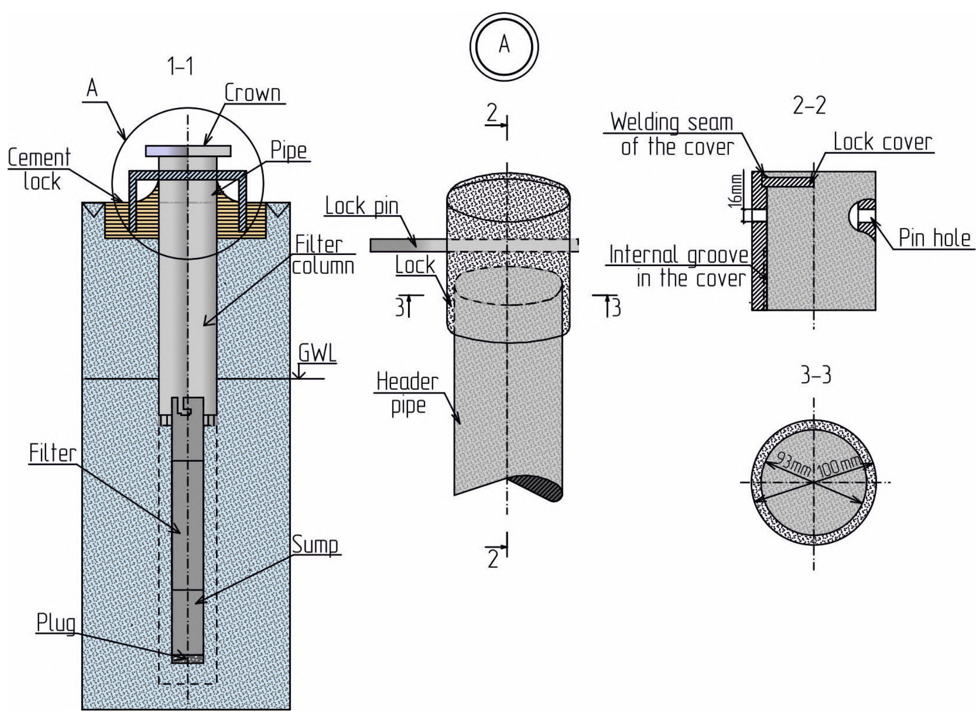

Figure 6. Design of observation boreholes.

characteristics, including time variability. In addition, the specificity of the storage facility is a change in their main technological parameters (elevation, impact area, etc.) during their service life, which, taking into account other factors and features mentioned above, introduces significant uncertainty into each of the indicators characterising the facilities' condition.

Considering that the designed tailings pond is a hydraulic structure, the material for which is the waste (tailings) stored in it, the reliability of the structure and the possibility of emergency situations depend on the quality of tailings alluviation and compliance with the specified design parameters (both physical and technological).

The following design case was considered for the stability of the downstream slope of Myroliubivka tailings pond (for all cross-sections): no water in the downstream, normal retaining level (NRL) in the upstream is assumed to be at its maximum position, and the dam body is considered to have installed filtration for the maximum design water level.

The following design cases are considered in determining the stability of the hydraulic dam in the vicinity of spillway 4:

- for the downstream slope – the main load combination; a dam with the 135.0 m crest, normal retaining level in the upstream, and filtration installed in the dam body;
- for the upstream slope, the construction period is designed: the main protection dam and the dams of the pools with the 135.0 m crest (at the end of washing out the last layer of the pools). The water level of the clarification pond (in the pool) is at 134.3m, the level of sludging the upstream slope with tailings is 133.75m), and filtration is installed in the dam body. At the base of the hydraulic dam, the tailings pond is washed out up to 121.6 m; the water level is at 122.5 m.

In determining the dam stability in the vicinity of spillway structure 3, the following design case is considered. As for the main load combination, the dam has a 125.0 m crest, a normal retaining level (123.5 m) in the upstream, and filtration in the dam body.

The dam stability is calculated by two programmes: the computer aided design system for ground hydraulic structures and the KZU86K programme developed by specialists of the VIOGEM Institute (the All-Russian Research Institute for Mineral Deposits Drainage, Protection of Engineering Structures from Flooding, Special Mining Works, Geomechanics, Geophysics, Hydrotechnics, Geology and Mine Surveying).

The computer-aided design system for soil hydraulic structures (CAD SHS) is designed to solve a number of problems in designing dams, dikes, upland ditches, sludge ponds, tailings dams and other structures [8].

The Terzaghi method provides lower safety factors for gentle slopes (1:2 or more), with a difference of 10...20%. The averaged slopes of Myrolubivka tailings pond are much gentler.

The desire to take into account all equilibrium conditions in the shear scheme leads to the emergence of such methods as the Mozhevytynov method (method of inclined interaction forces) and the finite element method (FEM).

The Terzaghi-Chuhaiev calculation method gives results intermediate between the Terzaghi and Chuhaiev methods. In accordance with the regulatory literature, the methods adopted in this study are allowed to be used in calculations.

All the described calculation methods refer to the case of a plane problem, i.e. it is assumed that no resistance forces occur along the lateral parts of a single slip or retaining prism along the front of the structure. In reality, slope failures are usually local and have a closed contour in plan view. Taking into account the spatial extent of sliding for conditions that are not variable along the length (front) of the structure leads to an increase in stability coefficients, and therefore, in these cases, solutions of the plane problem are usually used, which are included in the "stability margin".

The software allows performing stability calculations using the following methods:

- Terzaghi weight pressure method;
- Mozhevytynov method of inclined interaction forces, recommended by the standard;
- FEM (the finite element method).

The programme also allows performing filtration calculations necessary for calculating slope stability.

Filtration calculations determine the following parameters of the filtration flow:

- position of the filtration flow surface (depression surface);
- filtration water flow through the body of the structure and its foundation;
- pressure gradients of the filtration flow in the body and base of the structure at the boundaries of soils and media.

Filtration calculations are performed in accordance with the following regulatory documents.

Filtration calculations are performed using the FEM method based on the methodological recommendations for calculating the safety factor of slopes with a circular-cylindrical sliding surface using the KZU86K programme.

The programme allows defining a set of design slip curves (with safety factors) in a given slope range. This makes it possible to define both "general" and "local" slip curves.

Tasks solved by the programme include:

- determining the safety factor of the slope of the soil massif assuming arbitrary and circular-cylindrical sliding surfaces under static and seismic conditions, taking into account possible concentrated loads and pore pressure;
- determining all force characteristics for the selected sliding section (active and reactive forces on the covering footwall, column weights, distribution of filtration forces, etc.;
- solving the inverse problem (at a given stability factor of 1, it is determined by the strength of the slope soil property).

To obtain the desired result, a calculation algorithm is developed:

- select design materials for the construction of design diameters;
- draw geological sections on cross-sections;
- analyse the results of geological data and selected design characteristics;
- encode initial data for calculation for all cross-sections and interpret the geological data;
- enter the information into the calculation software;
- perform primary calculations using 4 methods (ITU, Mozhevytynov, Terzaghi, and Terzaghi-Chuhaiev) and 2 programs (CAD SHS, KZU86K) for all the dam sites (for the "general" curve and "local" curves);
- select the contours of additional loading of the downstream slope with intermediate calculations;
- analyse the results obtained.

The results of stability calculations are expressed as slip curves on the cross sections of Station (S) 39+00 (upstream and downstream slope) (figure 7, figure 8).

The results of calculations of the stability of the downstream dam slopes, with the selection of minimum safety factors determined for the "general" curve, are shown on the design sections.

The minimum safety factors of the "general"/"local" curve for the main combination of loads in the calculation of the stability of the lower slopes of dams are as follows:

- for S 8+50 according to the methodology: Mozhevytynova (1.501 / 1.568), FEM (1.522 / 1.423), Terzaghi (1.417 / 1.45), Terzaghi-Chuhaieva (1.53 / 1.58);
- for S 19+00 (upper) by methods: Mozhevytynova (1.638 / –), FEM (1.474 / –), Terzaghi (1.231 / –), Terzaghi-Chuhaieva (– / –);

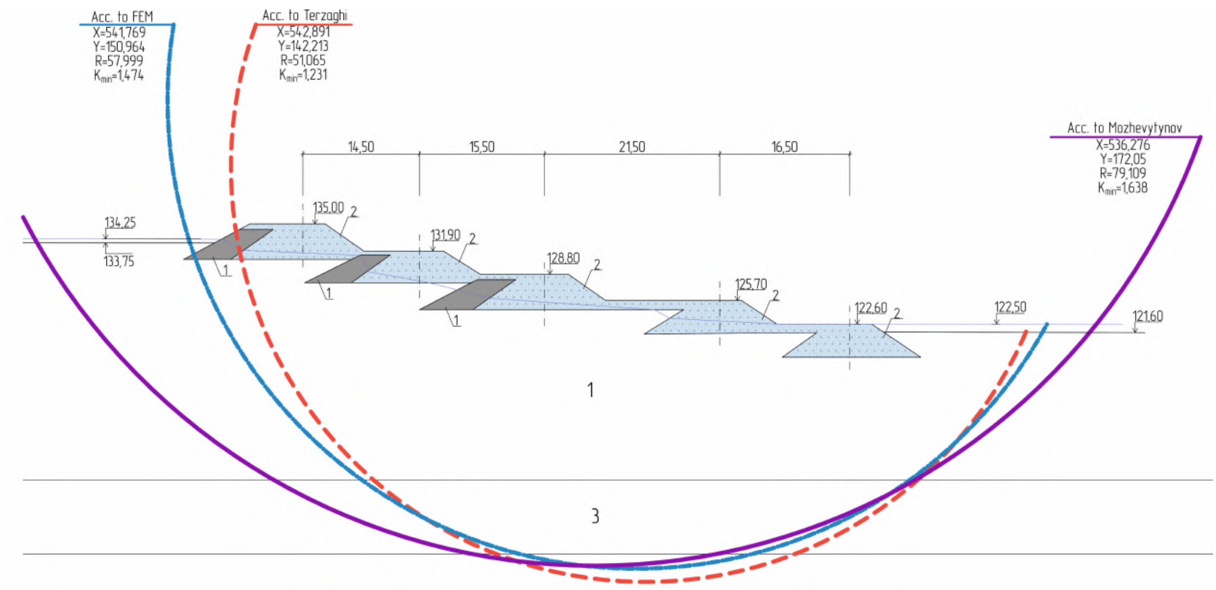

Figure 7. Results of stability calculations (upstream slope of the S 39+00 cross section): 1 – silt washed-in tailings; 2 – rocky overburden; 3 – loam washed-in tailings.

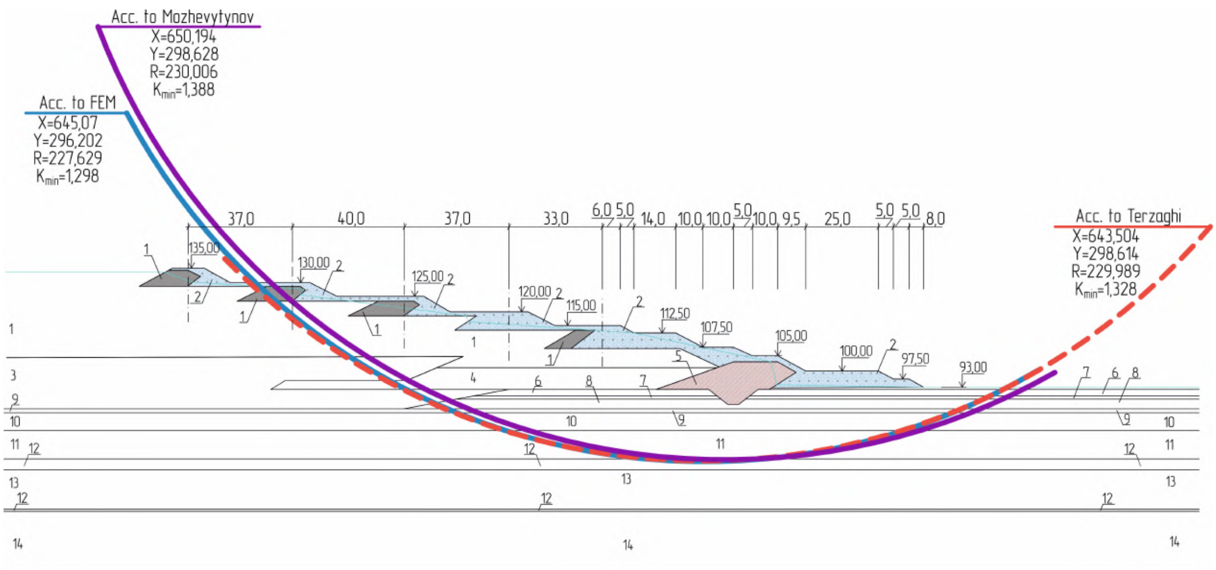

Figure 8. Results of stability calculations (downstream slope of the S 39+00 cross section): 1 – silt washed-in tailings; 2 – rocky overburden; 3 – loam washed-in tailings; 4 – small washed-in tailings; 5 – filled soil – clay in the body; 6 – loess, heavy, silt, red-brown loam; 7 – hidden soil, silt heavy loam; 8 – loess, heavy, silt, yellow-brown loam; 9 – hidden soil, heavy loam; 10 – heavy, red-brown loam; 11 – light, silt, ocher-red clay; 12 – heavy, silt, green-gray clay; 13 – fine sand with a layer of loamy sand and loam; 14 – light, green-gray, light gray clay.

- for S 19+00 (lower) by methods: Mozhevytynova (1.388 / –), FEM (1.298 / –), Terzaghi (1.328 / –), Terzaghi-Chuhaieva (– / –);
- for S 24+25 by methods: Mozhevytynova (1.5 / 1.488), FEM (1.471 / 1.484), Terzaghi (1.437 / 1.411), Terzaghi-Chuhaieva (1.49 / 1.42);

- for S 27+50 by methods: Mozhevytynova (1.265 / 1.048), FEM (1.208 / 1.166), Terzaghi (1.143 / 1.055), Terzaghi-Chuhaieva (1.26 / 1.27);
- for S 31+00 by methods: Mozhevytynova (1.366 / 1.551), FEM (1.335 / 1.527), Terzaghi (1.313 / 1.44), Terzaghi-Chuhaieva (1.37 / 1.58);
- for S 33+80 by methods: Mozhevytynova (1.785 / 1.618), FEM (1.871 / 1.630), Terzaghi (1.722 / 1.503), Terzaghi-Chuhaieva (1.71 / 1.38);
- for S 34+60 by methods: Mozhevytynova (1.637 / 1.003), FEM (1.601 / 0.98), Terzaghi (1.576 / 0.888), Terzaghi-Chuhaieva (1.66 / 1.08);
- for S 42+96.6 by methods: Mozhevytynova (1.553 / 1.444), FEM (1.494 / 1.561), Terzaghi (1.501 / 1.53), Terzaghi-Chuhaieva (1.52 / 1.51);
- for S 51+60 by methods: Mozhevytynova (1.742 / 1.218), FEM (1.726 / 1.25), Terzaghi (1.667 / 1.08), Terzaghi-Chuhaieva (1.55 / 1.53);
- for S 55+25 by methods: Mozhevytynova (1.477 / 1.626), FEM (1.427 / 1.585), Terzaghi (1.428 / 1.487), Terzaghi-Chuhaieva (1.53 / 1.46);
- for S 61+07.5 by methods: Mozhevytynova (1.554 / 1.505), FEM (1.498 / 1.475), Terzaghi (1.462 / 1.445), Terzaghi-Chuhaieva (1.49 / 1.5);
- for S 69+02.2 by methods: Mozhevytynova (1.471 / 1.49), FEM (1.561 / 1.645), Terzaghi (1.437 / 1.433), Terzaghi-Chuhaieva (1.62 / 1.65);
- for S 72+60 by methods: Mozhevytynova (1.622 / 1.738), FEM (1.62 / 1.753), Terzaghi (1.565 / 1.582), Terzaghi-Chuhaieva (1.62 / 1.52).

In calculations of the stability of the downstream dam slopes of dams, the position of the depression curve (the position of the filtration flow surface) is taken on the basis of CAD SHS-based filtration calculations.

A comparative analysis of the calculation results of the stability of the downstream slopes shows comparatively close values of the obtained coefficients and the correctness of the choice of calculation methods as the most commonly used in practice.

Analysis of the actual condition of hydraulic structures, taking into account the calculations performed, drawing the following conclusions about Myroliubivka tailings storage facility:

- The reliability of the downstream slope of the tailings dam at Myroliubivka tailings storage facility is assessed in accordance with regulatory requirements;
- Most calculated cross-sections, according to all the methods used to calculate the downstream slope, have a safety factor (both for general and local stability) that is higher than the minimum required by the standard;
- For certain cross-sections, minimum safety factors determined are less than the required standard values. For these sections, additional measures to ensure standard stability are required;
- According to the standard, Kryvyi Rih is classified as an area with a seismic intensity of 6 points. Soil conditions at Myroliubivka tailings pond are classified as category III. At the same time, the overall seismicity of the area is 6 points and it does not fall within the seismicity standard. On this basis, no seismic stability checks are performed at this stage of work.

Recommended measures include:

- All hydraulic structures of Myroliubivka tailings facility should be subjected to constant monitoring of the dam condition, compliance with design requirements for tailings allocation technology, the degree of wear of pipelines (especially those passing through dams and in the vicinity of hydraulic structures), and compliance with design water levels in the tailings facility;

- To ensure the required reliability of the tailings facility, it is proposed to construct a special type of retaining wall in the area with the lowest safety factor for the period of dam operation [9, 10].

The proposed prefabricated block-type retaining wall (figure 9, figure 10) consists of a foundation slab and a vertical element presented in the form of concrete or reinforced concrete blocks mounted on top of each other, the front face of each of them is made straight, and the back face is in the form of a structural surface of pyramids. The foundation slab of the retaining wall is equipped with piles located directly under the base of the foundation slab.

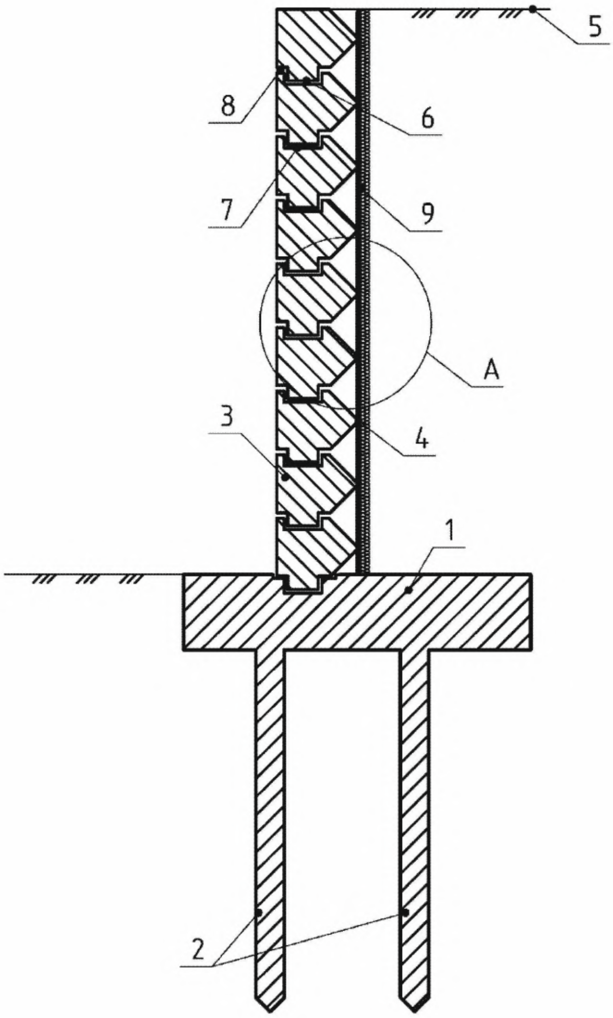

Figure 9. Prefabricated block type retaining wall: 1 – foundation slab; 2 – piles; 3 – blocks; 4 – surface in the form of pyramids; 5 – soil; 6 – spikes; 7 – groove; 8 – high-strength solution; 9 – two sheets of flexible, resilient material.

To prevent premature filling of the cavities, two flexible separating sheets of elastic and pliable material made of a biodegradable polymer are placed on the back surface of the vertical element.

The proposed prefabricated block-type retaining wall consists of a foundation slab 1 with piles 2 and a vertical element made of blocks 3 stacked one on top of the other. The vertical element includes front and back faces. The front face of blocks 3 is rectilinear, and the back face is in the form of a structural surface, which is a protruding pyramid 4 from the side of retained

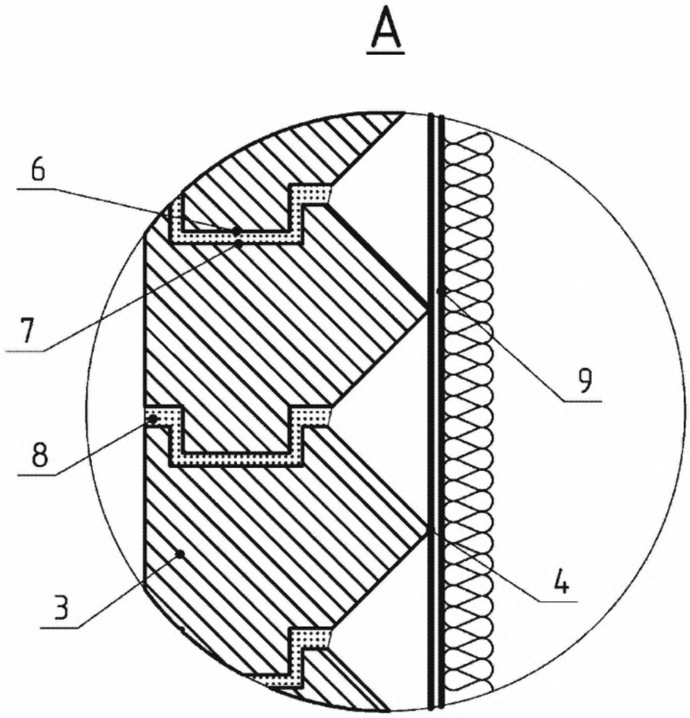

Figure 10. Node A: 3 – blocks; 4 – surface in the form of pyramids; 6 – spikes; 7 – groove; 8 – high-strength solution; 9 – two sheets of flexible, resilient material.

soil 5. The blocks are mounted one on top of the other and interconnected by spikes 6 that fit into grooves 7 on high-strength mortar 8. On the back face of the vertical element, there are two sheets of flexible, resilient material 9 made of biodegradable polymer.

To connect the vertical element consisting of blocks 3 to main slab 1, a block with a straight front face, a pyramidal back face, spike 6 on the lower surface and groove 7 on the upper surface is used. The main components of the vertical element are blocks with a straight front face, a pyramidal back face, groove 7 on the upper surface and spike 6 on the lower surface. The vertical element is completed with a block with a rectilinear front face, a pyramidal back face and spike 6 on the lower surface.

Stability of the retaining wall is ensured by piles 2, spikes 6 and grooves 7 of blocks 3. Blocks 3 can be connected with high-strength mortar 8. The surface in the form of pyramids 4 of blocks 3 in contact with soil 5 significantly reduces the horizontal pressure of soil 5, redistributing it along the height of the retaining wall. The effect increases with active shear of soil 5.

The back surface of the vertical element has two sheets of resilient material 9. Sheets 9 are arranged in two rows and uniformly compact the backfill soil, with the first sheet serving as an anti-friction coating to reduce friction forces. The sheets are made of modern materials that are completely decomposed by microorganisms under aerobic or anaerobic conditions into carbon dioxide, methane, water, biomass and inorganic compounds.

The polymer decomposition period depends on the length and structure of the polymer chain, which in turn makes it possible to select the required polymer composition to perform the tasks set throughout the entire service life of the block retaining wall. Reduction of the polymer chains leads to a loss of mechanical properties (strength, tensile strength, bending strength). Therefore, the sheets of elastic-responsive material 9 are selected as follows: the first sheet from the retaining wall is thinner, but with longer polymer chains, the second sheet is thicker, but with shorter polymer chains, so that the first sheet will perform the function of an antifriction coating for a longer time, and the second sheet will absorb and redistribute the forces from horizontal movement of the soil by decomposing faster than the first one.

This structure is able to withstand significant shear loads and forces from horizontal ground displacement for an even longer period of time, which extends its service life.

The proposed prefabricated block-type retaining wall can be used to stabilize unstable slopes, while the foundation slab, piles and blocks of the vertical element can be unified.

The block-type prefabricated retaining wall can withstand significant shear forces arising from the operation of unstable slopes, as well as horizontal ground movements during excavation.

The proposed structure can be used to stabilize unstable slopes, while the foundation slab, piles and vertical element blocks can be unified. It is highly reliable when operating in a critical situation of an unforeseen emergency increase in the shear force load. The installation of this structure will provide additional stability of the hazardous area of the tailings pond and will guarantee the reliability and operational longevity of the tailings pond (figure 11, figure 12, figure 13).

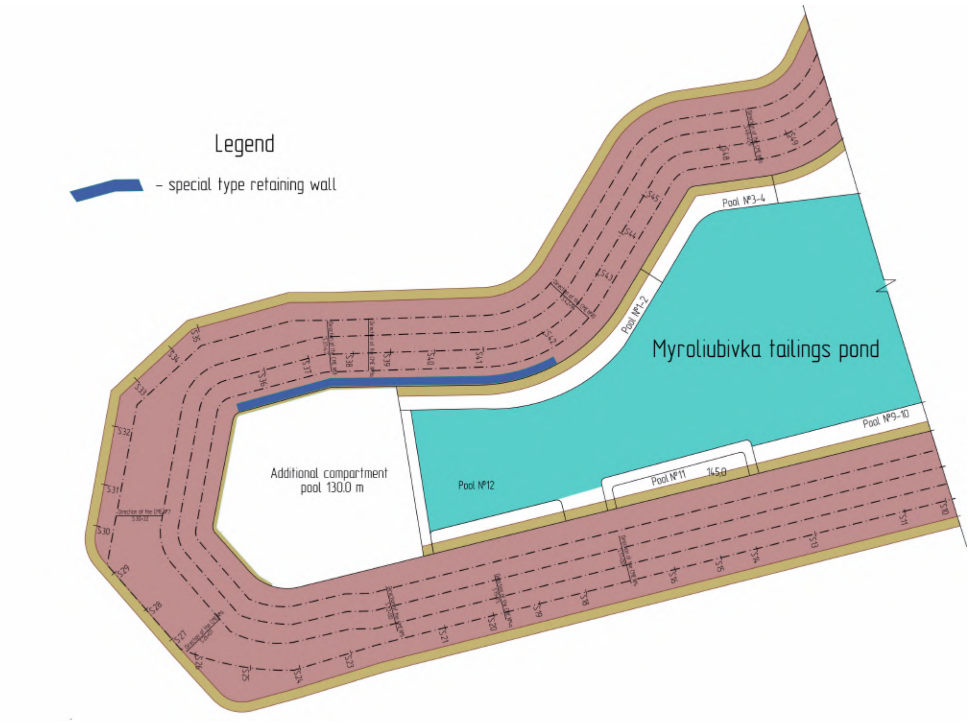

Figure 11. Retaining wall area.

The paper analyses experimental and theoretical studies of distribution of sliding planes in multilayer backfill of retaining walls in the absence and presence of different strip loads on this surface. These studies indicate that horizontal shear of the entire wall or any of its upper parts leads to the formation of a single shear plane under not only complex but also concentrated loads on multilayer backfill. Moreover, this effect does not depend on the sequence of layers with different physical and mechanical characteristics φ and γ along the backfill depth.

Adoption of a single sliding plane for each depth of the retaining wall allows presenting a calculation scheme for determining the horizontal pressure (figure 14) and formulate new principles for determining the horizontal pressure on the retaining wall, taking into account the multilayer backfill and the load on the surface in accordance with the standard [11].

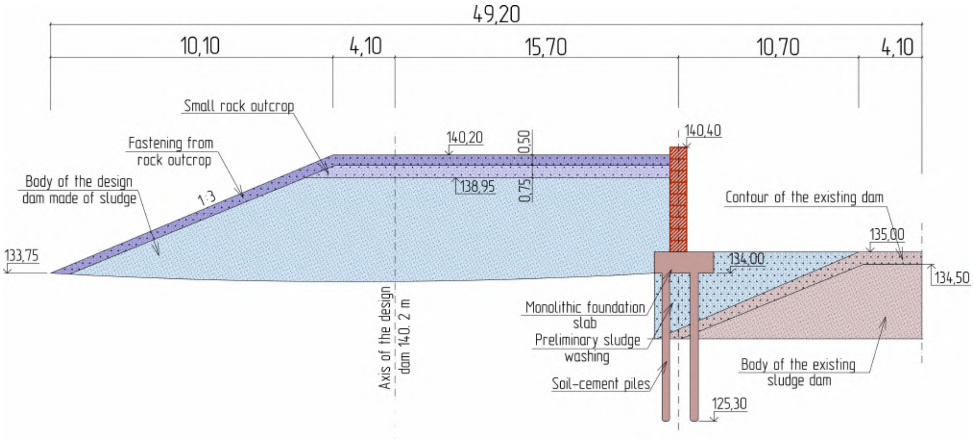

Figure 12. Installation of a prefabricated retaining wall.

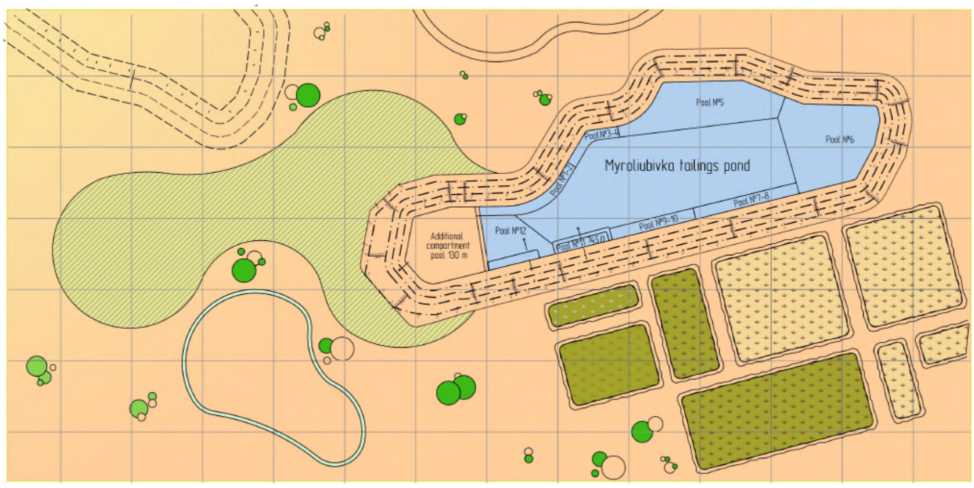

Figure 13. Flooding area in case of a potential failure.

4. Conclusions

Myroliubivka tailings pond is an engineering structure of the first category of responsibility and currently requires new approaches, as well as changes in technology to ensure its stability during long service life.

Available calculation methods based on the theory of linearly deformed media do not fully meet the operating conditions.

Therefore, consideration of the influence of a multilayer nonlinearly deformed massif under external loading allows formulating new principles for determining the horizontal pressure on the retaining wall, namely:

- the mass of sowing between the wall and the shear plane is divided into separate prisms resting within each layer hi on the collapse plane;
- the prisms are divided by vertical planes extending from the intersection of the collapse area with the boundaries of the soil layers to the backfill surface (in areas of loaded surface) or to the footwall of the local load;
- part of the distributed load located on any prism is summed with the weight of this prism, i.e. included in the value Gi;

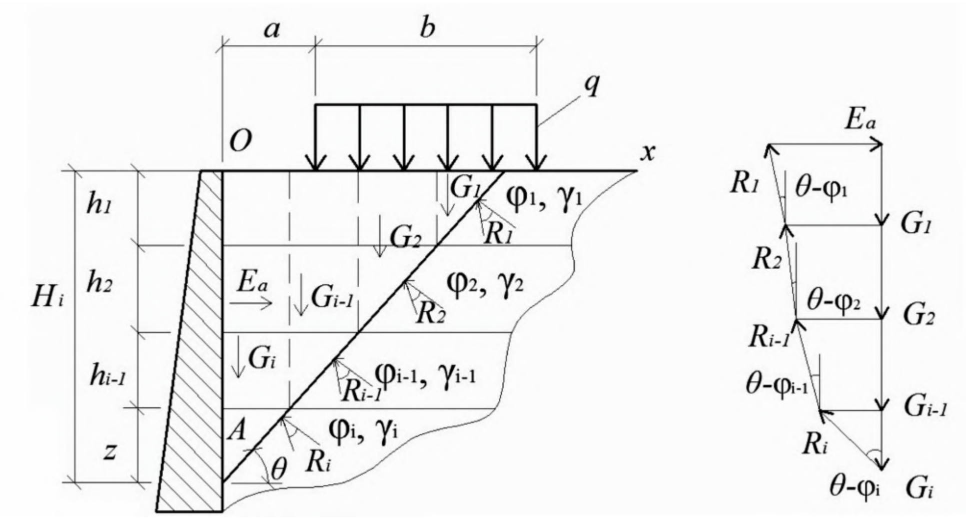

Figure 14. Design diagram of a retaining wall with multilayer backfill and surface load.

- interaction of prisms along vertical planes is not taken into account;
- each depth has its own collapse area, the position of which does not depend on the total wall depth Hmax.

Application of a special type of retaining wall allows obtaining an economic effect due to both the design solution and the extension of the service life.

The effectiveness of the existing system for protecting the aquatic environment (primarily groundwater) from pollution by the Mirolyubovskoye tailings dump in the area under consideration is estimated at 87 percent.

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The usage of GIS in the retrospective analysis of the territorial organization of Kryvyi Rih settlement

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Abstract. The article presents the retrospective analysis of the territorial organization of the settlement of Kryvyi Rih territory on the basis of a detailed study of topographic maps of various historical periods, namely, the Map of the Polish-Lithuanian Commonwealth, the Special Map of the Western Part of the Russian Empire by F. Schubert, Three-mile military topographic map of the Russian Empire, the Maps of the Office of Military Topographers of the Red Army, the Maps of the German Army, Topo maps of the US Army and Maps of the General Staff of the USSR Armed Forces. The research is based on the authors' method of retrospective modeling of the historical settlement of the region using historical topographic maps of various time periods and their complex analysis by means of GIS. The results of the research constitute the model of the territorial organization of the settlement process in Kryvyi Rih region. The model represents the historical population resettlement in the studied region and indicates the spatiotemporal changes of the following indexes: the nature and number of settlement locations, the size of settlements, number and density of the population, the ratio of rural and urban populations, etc. The obtained cartographic materials and demographic indicators of resettlement at various times make a significant contribution to the historical and geographical research of the region.

1. Introduction

1.1. The problem statement

The multifaceted studies of geographical landscapes stipulate special attention to the retrospective research featured by spatio-temporal combinations. As Langton [1] noted, instead of simply comparing isolated systems in equilibrium, i.e. performing so-called "synchronistic analysis", researchers must be able to study processes retrospectively by "slicing successive series of synchronous images of systems" through time.

The study of landscape dynamics is extremely important for determining the anthropogenic impact on the transformation of technogenically disturbed geosystems. Kryvyi Rih constitutes a vivid example of such an anthropogenically disturbed geosystem, as for more than 130 years, it has been excessively mined and minerals (iron ores) have been processed in extremely large volumes.

Within the scope of this publication, we consider Kryvyi Rih region as a conditional territorial unit of geographic zoning, which boundaries coincide with the borders of the Kryvyi Rih natural and economic district [2].

The territorial organization models of the settlement process in a respective region reflects the experience of interaction in the human-nature system. The above-mentioned models are formed in the process of historical resettlement of the population in a certain territory and are characterized by spatio-temporal changes, such as: the totality and size of settlements, the number and density of the population, the share of the rural and urban population. Retrospective studies of the territorial organization of a settlement can reveal the cause-and-effect relations between geodemographic and anthropogenic processes, and therefore, implement a scientifically based policy of socio-economic development of the territory.

Retrospective studies are grounded on the spatial multitemporal and attributive materials to form a wide information field. Therefore, GIS technologies enable a quick and high-quality analysis of spatial and temporal changes in territories. The advert of a new type of GIS (historical-landscape) makes it now possible to visualize a clear picture of the development of territories in different historical periods. So, "cross-cutting" historical-landscape analysis explores the territory, the dynamics of its landscape and economic activity with the subsequent compilation of a number of maps, different in chronology [3].

1.2. Theoretical background

The extensive analysis of the scientific literature has established the following three research directions:

1) scientific investigations of the system of population resettlement analysis;
2) retrospective studies of regional settlement systems of individual territories;
3) historical and geographical works on the process of formation of settlements within Kryvyi Rih area.

The population resettlement system is presented in many general-theoretical and regional-practical works of Langton [1], Denysyk et al. [4], Dzhaman [5], Illiash and Tkach [6], Topchiiev [7] and Boudeville [8]. The authors mostly characterize various aspects of the functioning of territorial structures, models of spatial arrangement of settlements, resettlement and migration of the population, etc.

The retrospective studies on the regional population settlement systems [9–17] focus on identification of the features of the historical settlement of territories depending on their socio-economic development. The focal point of these publications is both various regions and different approaches to delineating the historical retrospective.

The formation of settlements within the territorial structure of Kryvyi Rih is described in a number of historical and geographical studies [18–25]. The above-mentioned works substantiate historical stages of the development of the region on the basis of archival sources, as well as present accounting and statistical materials of individual settlements.

The analysis of scientific research has established significant achievements in the study of population displacement in its historical retrospect, but also revealed certain gaps concerning such important aspects as the identification of spatio-temporal changes in the displacement of the population of Kryvyi Rih region and the anthropogenic activity impact caused by centuries-long extraction of useful fossils.

1.3. The objective of the article

The purpose of the publication is to reconstruct the anthropogenic effect on the transformation of natural landscapes by means of a retrospective analysis of the process of territorial organization of Kryvyi Rih settlement.

The primary purpose comprises three following research tasks:

1) to determine the chronological limits of the formation of settlement landscapes on historical maps of Kryvyi Rih at various times;
2) to develop a methodology for modeling the historical settlement of Kryvyi Rih territory;
3) to conduct a retrospective analysis of the settlement process of Kryvyi Rih territory using GIS.

2. Methods

2.1. Factual research material

The retrospective research admittedly uses two main sources of information which reflect the state of the territory in a certain period of time: various historical texts (primary sources and historiography) and cartographic materials of different times.

This publication uses a number of historical text materials that reflect the development of Kryvyi Rih area. However, we note that these sources provide unsystematic and episodical accounts of the settlement of the territory of the studied region and mostly without spatial visualization. The analyzed material sometimes manifest significant content contradictions, which require further determination of the validity of the presented spatio-temporal data.

Cartographic materials of the studied territory are represented by a number of historical maps created over three centuries of topographic research. The main ones are: Map of the Polish-Lithuanian Commonwealth, Special map of the Western part of the Russian Empire by F. Schubert, Three-mile military topographic map of the Russian Empire, the Maps of the Office of Military Topographers of the Red Army, the Maps of the German Army, Topo maps of the US Army and Maps of the General Staff of the USSR Armed Forces. We utilized these maps as primary tools for assessing the anthropogenic transformation of the territory, because they recorded all environmental changes.

The presented scientific research is the extension of the team study of co-authors [26], which evaluates and compares different temporal cartographic materials in view of their accuracy and reliability. In particular, different temporal topographic maps of Kryvyi Rih area are considered as an information resource for retrospective studies. We also carry out the additional research which determines the chronological intervals of correspondence of the data applied to cartographic works, and thus to select reliable cartographic material (table 1). Meanwhile, the study of historical maps of Kryvyi Rih arises a number of challenges, such as: map poor-quality depiction (crumpled and worn sheets, unclear printing, etc.); different mapping and nomenclature of maps cause variation of location of the research area in different sources (on one or several sheets); on most maps, the legend is missing or presented in a very simplified version; maps differ significantly in terms of their mathematical basis (scale, longitude, cartographic projection, length measurement system, etc.); the maps differ significantly in toponymy (for example, the modern name of the village *Sofiivka* has undergone the following changes since its foundation to the present day: *Sofievka, Sofievo-Geikivka, Sofievo, Valove*). The described difficulties significantly complicated the analysis of spatial indicators of different time cartographic works.

2.2. Research methodology

Establishing the historical process of settlement of Kryvyi Rih territory requires to determine the time of origin and location of settlements within the region, and to characterize their demographic indicators at different times (population of settlements, number of yards, etc.).

The specified methodology supposes to analyze the cartographic works of various times and to determine the nature of the settlement placement using a system of conventional signs. However, as established earlier [26], the date of publication of most maps of Kryvyi Rih region does not correspond to the time of topographic surveys. Predominantly the basis of the studied maps were older cartographic materials with changes and clarifications with the period of inconsistency ranging from 10 to 30 years, or even longer. Therefore, with a view to accurately determine the spatio-temporal characteristics of the studied objects marked on the maps, we exploit a comparative analysis of the information given in various historical sources.

For example, figure 1 shows a diagram illustrating the quantitative changes of the yards in the Kryvyi Rih settlement at the end of the 18th century – the end of the 19th century. The plotted data on the number of yards in Kryvyi Rih, obtained from the Special Map of the Western part of the Russian Empire by F. Schubert, created in 1849, shows 460 yards. Yet the updated Three-mile military topographic map of the Russian Empire, corrected on the results of the 1888 survey, there are 770 yards. So, we can conclude that the data visualized on the Schubert map correspond to 1810, and on the Three-mile map to 1882.

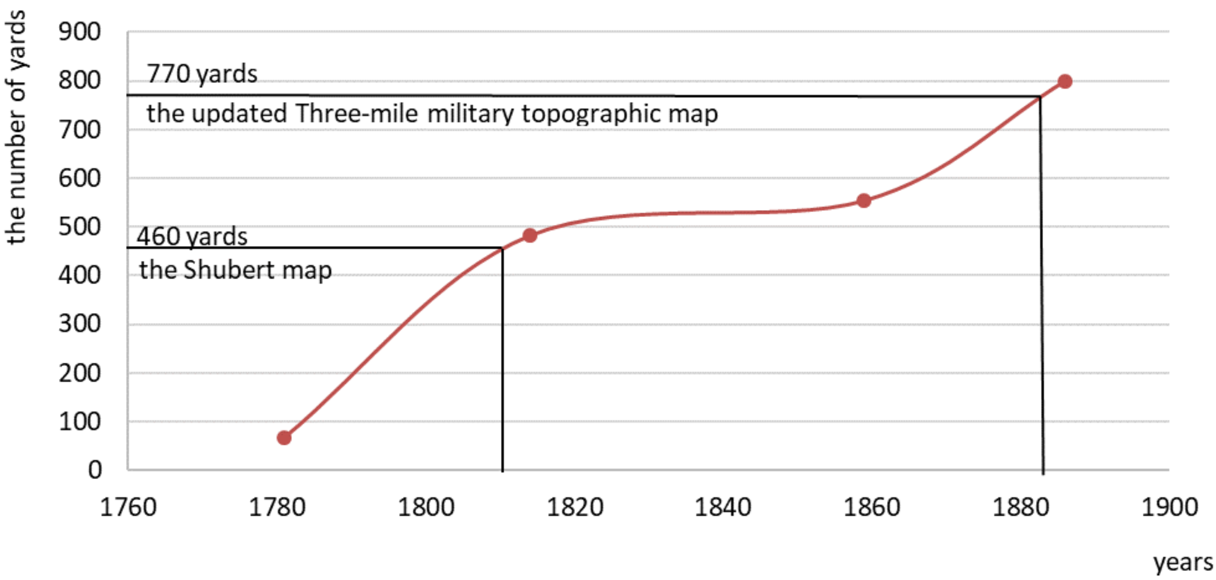


Figure 1. Diagram of changes in the number of yards in Kryvyi Rih from the end of the 18th to the end of the 19th century.

We make similar diagrams for other "cross-cutting" settlements (Lozuvatka, Nedayvoda, Shiroke, etc.), which help determine the temporal intervals of correspondence of the data plotted on these maps (table 1).

Analogically, the population of Kryvyi Rih city on the map of the General Staff of the USSR Armed Forces, created in 1990, corresponds to the time range of 1985-1987 (figure 2).

The most obvious findings to emerge from the analysis of different time maps of Kryvyi Rih are as following:

1. The map, identified by historical sources as the map of the Polish-Lithuanian Commonwealth, dated the end of the 17th century, is an exact copy of F. Schubert's Special Map of the Western Part of the Russian Empire with designations of settlements in Polish and the use of specific conventional signs. In order to use it in our research as cartographic basis of the end of the 18th century period, we performed some corrections to remove objects belonging to another time interval.
2. The tactical map of the German army, created in 1942, is used to analyze the settlement of Kryvyi Rih in the 1st half of the 20th century. It was built on the basis of the Map of the Office of Military Topographers of the Red Army (1930) and the Map of the General

Table 1. Time intervals of correspondence of data presented on different time maps.

№	Map name*	Data matching time intervals
1	Map of the Commonwealth of Nations	corrected at the end of the 18th century
2	A special map of the Western part of the Russian Empire by F. Schubert	1810–1820
3	Updated three-mile military topographical map of the Russian Empire	1880–1886
4	Map of the German army	1930–1931
5	Map of the General Staff of the USSR Armed Forces	1982–1986

* - detailed characteristics of the maps (year of creation, scale, projection, average relative error, etc. [26]

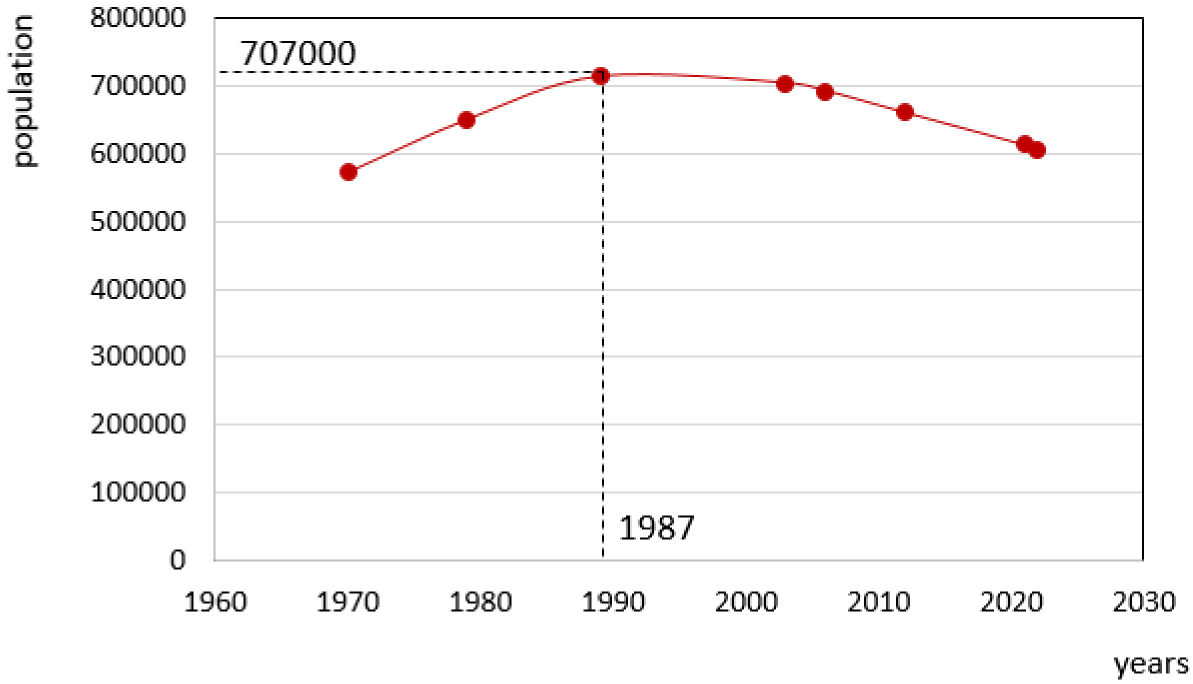


Figure 2. Chart of population changes in the city of Kryvyi Rih from 1970 to 2021.

Staff of the Red Army (1931) without reconnaissance. As a result, it did not reflect the changes occurred in the region for more than 10 years of active settlement. For example, the Karachuniv reservoir, which construction started in 1932, is not marked on the map. Accordingly, that map of the German army contains information from the 30s of the 20th century (table 1). Beyond that, the lack of accounting and statistical data for the stated period made it impossible to quantitatively analyze the features of the settlement of the population in the region.

The retrospective analysis enables to consider the facts depicted on these maps in accordance with certain periods of the region's development.

Quantitative characteristics of various temporal indicators of the studied territory demonstrates almost the absence of systematic and full-flegged information about the specifics of the population settlement of Kryvyi Rih area in certain periods of time, despite a significant number of historical documents.

We pay special attention to conflicting data present in various historical materials regarding the population (both of the region in general and of individual settlements) in different periods of the settlement of Kryvyi Rih area. To fill the identified gaps, we additionally study historical documents in order to establish the correlation between the number of yards and their population on the territory of residence. However, the calculations do not take into account the indicators of large settlements, such as Kryvyi Rih, Lozuvatka, etc., since the historical and statistical information about them is quite detailed. The result of the data obtained on the basis of the analysis of accounting and statistical information is the linear diagram presented in figure 3.

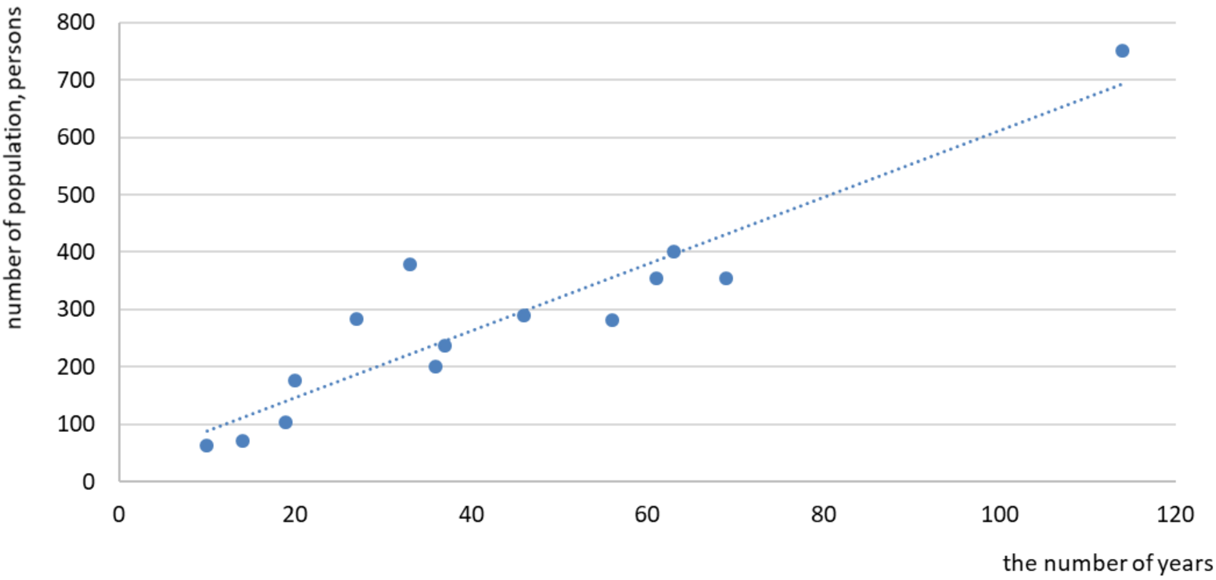


Figure 3. The relationship between the number of yards and the population of the villages of Kryvyi Rih area at the beginning of the XIX century.

The diagram shows the close correlation between the number of yards and their population on the territory of residence according to the pairwise correlation coefficient is +0.89. So, the number of yards in Kryvyi Rih area allows to calculate with a high degree of reliability spatio-temporal indicators of the population for all analyzed time segments. A spot check of the obtained results based on historical materials confirms their accuracy, since the error did not exceed 5% for settlements with up to 100 yards.

The peculiarities of the processing of spatial and attributive data of various time periods by means of GIS technologies deserve particular characterization. Topographic maps of the region at various times were used as basic spatial materials for the geo-informational analysis of the territory of Kryvorizhzhia (table 1).

At the first stage, we "stitch" the map sheets, since the entire territory of Kryvyi Rih is placed on two sheets (e.g., the map of the German army) and four sheets (e.g., the updated Three-Mile military topographic map of the Russian Empire).

At the second stage, the raster image of the maps is linked to the free access GIS – QuantumGIS. This stage challenge is connected with binding to one modern topographic basis, since all cartographic materials differ significantly in their mathematical basis.

Particularly, on the Map of the General Staff of the USSR Armed Forces (scale 1:100000), binding of sheets was carried out by an array of registration points (from 20 to 45) depending on the scale and projection of historical maps, as well as their location on the base map. We use as registration points the points marking the settlements of the region and the elements of the relief of the area. Despite the large number of registration points, we make coordinate correction of the points on the retrospective maps during the binding. The resulting error ultimately ranges from a few tens of meters on the Map of the German Army to 200 meters on the Special Map of the Western Part of the Russian Empire by F. Schubert. Taking into account the low accuracy of old maps and the specifics of their mathematical basis, the obtained results should be considered sufficient for the historical and landscape analysis of the territory.

At the third stage, we make vectorization of the locations of settlements on all historical maps and fill in the corresponding attributive tables with established statistical demographic indicators (number of yards, population size, sex-age ratio, etc.). As a result, the primary retrostructural GIS model of Kryvyi Rih area was formed.

Geoinformational analysis of primary layers includes interpolation by the method of inverse distance weighting (IDW), construction of heat maps (estimation of core density), drawing of isolines, application of cartodiogram method, etc. [27–29]. Overall, a common workspace of more than 40 maps were created, which serve as a basis for the analysis and substantiation of the study conclusions.

3. Research results

Despite the tendency of a settlement system to sustainability resulting from the relative stability of the historical framework of the settlement network [11], it undergoes some dynamic changes during its development (new settlements appear, the old ones disappear, changes in their size, status, etc.). Therefore, throughout each historical stage a region forms its own settlement system, which reflects the local natural-geographic and socio-economic features of the development of the region (figure 4, figure 5).

The resettlement of Kryvyi Rih area actually began in the middle of the 16th century, when the territory became part of the territory of the Zaporizhzhia Nizovy Host, where it remained until 1775, the end of the Zaporizhzhia Army existence. At that time, there were about 10 winter camps with a population of at least 120 people within the boundaries of modern Kryvyi Rih area [25].

After the extermination of the Zaporozhian domains, the region was declared the property of the royal treasury. Part of the Zaporizhzhia people moved to a settled way of life in the newly created villages. However, active settlement of Kryvyi Rih area was observed since 1771, when the government of Tsarist Russia began distributing land to officers, former Cossack foremen, Russian, Ukrainian and Polish landowners. Thus, General Rakhmanov founded the village of Rakhmanivka, and Cornet Gdantsev founded the village of Gdantsivka. The founders resettled in the villages their serfs from other settlements in Russia and Ukraine. In addition, a significant share of state lands was sold to peasants and freed serfs [21]. This is the way how the settlement system of the region was formed at the end of the 18th century.

The analysis of the map of the Polish-Lithuanian Commonwealth (with the correction of the territorial distribution of settlements at the end of the 18th century) by means of the heat map method demonstrates the linear nature of the spatial distribution of settlements without the formation of concentration nodes (figure 4A). The increase in the density of settlements near Kryvyi Rih is exceptional. The settlements are quite distant from each other: the average distance between them is 7.9 km (figure 6), the total number of settlements in this period is 25 (figure 7), and the density of settlements was 1 per 152 km^2 of the area.

The linear nature of settlement is due to the localization of all settlements along the riverbeds of the Ingulets, Saksagan, Kamianka and Bokova rivers (figure 8). So, we can conclude that the

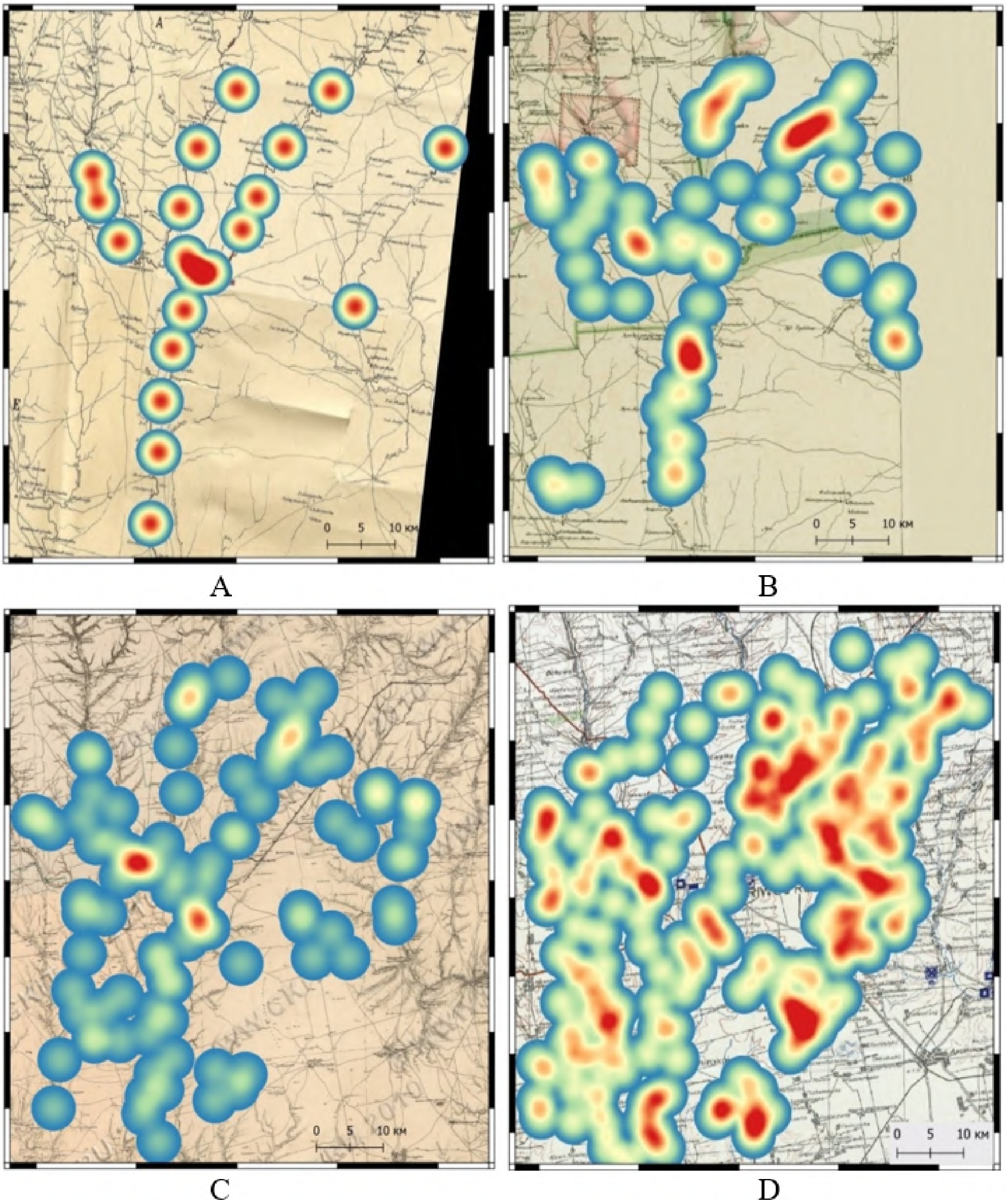


Figure 4. Thermal maps of the location of settlements in Kryvyi Rih area in different historical periods *(A – map of the Polish-Lithuanian Commonwealth; B – Special map of the Western part of the Russian Empire by F. Schubert; C – Updated three-mile military Topographical map of the Russian Empire; D – Map of the German army).*

natural factors, primarily the proximity of the river network, prevailed during the formation of a peculiar settlement structure at the end of the 18th century, as people chose fertile lands near

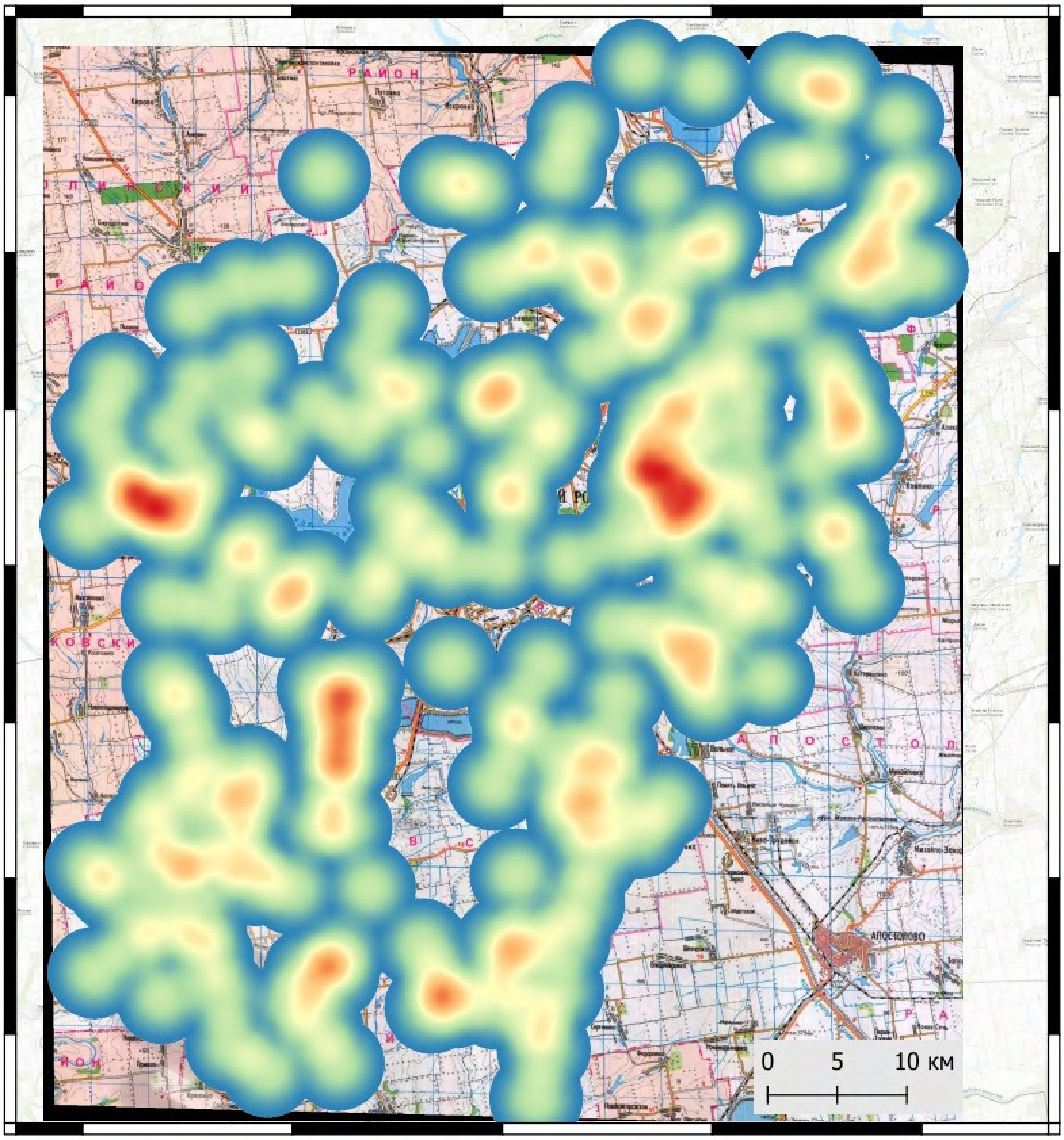


Figure 5. Map of the General Staff of the USSR Armed Forces.

rivers for settlement.

Quantitative composition of the population of Kryvyi Rih area at the end of the 18th century (figure 9A) shows the formation of two centers of development: Kryvyi Rih – in the center of the region and Lozuvatka – in the north. Their population significantly exceeds the one in other settlements. Thus, 762 people lived in Kryvyi Rih, and 353 in Lozovatka, the average population in other settlements was 30 people, which is visualized on the heat map (figure 9). The map demonstrates the uniform distribution of the population at that time, apart from the village of Zelene with the minimum number of people (7 people), and the village of Sofiivka with the maximum (67 people).

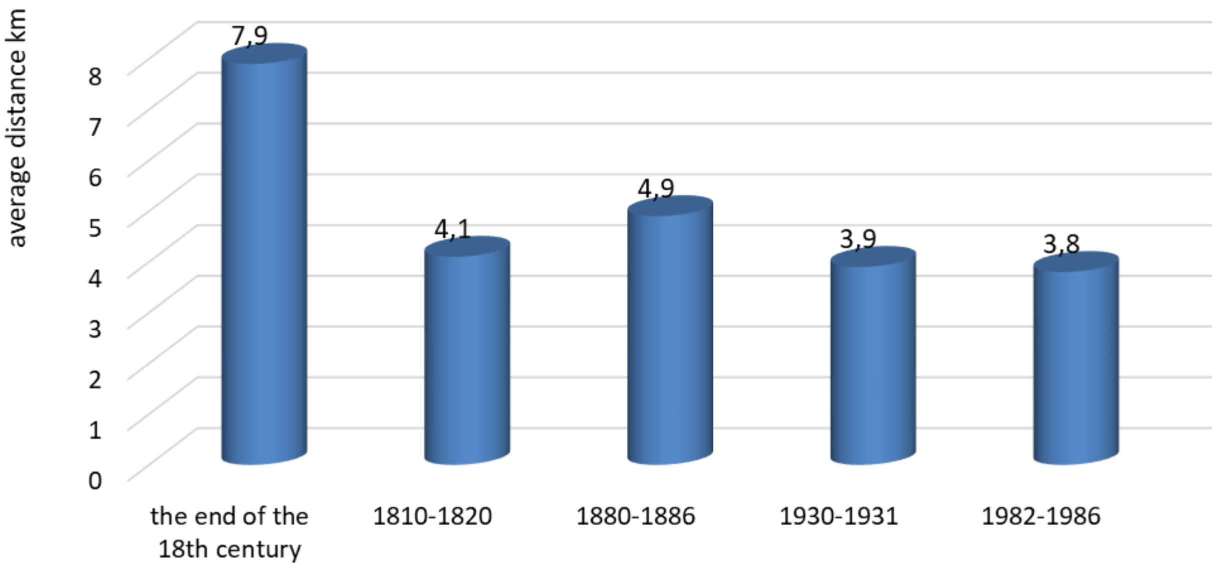


Figure 6. Change in average distances between settlements in Kryvyi Rih in different periods of settlement.

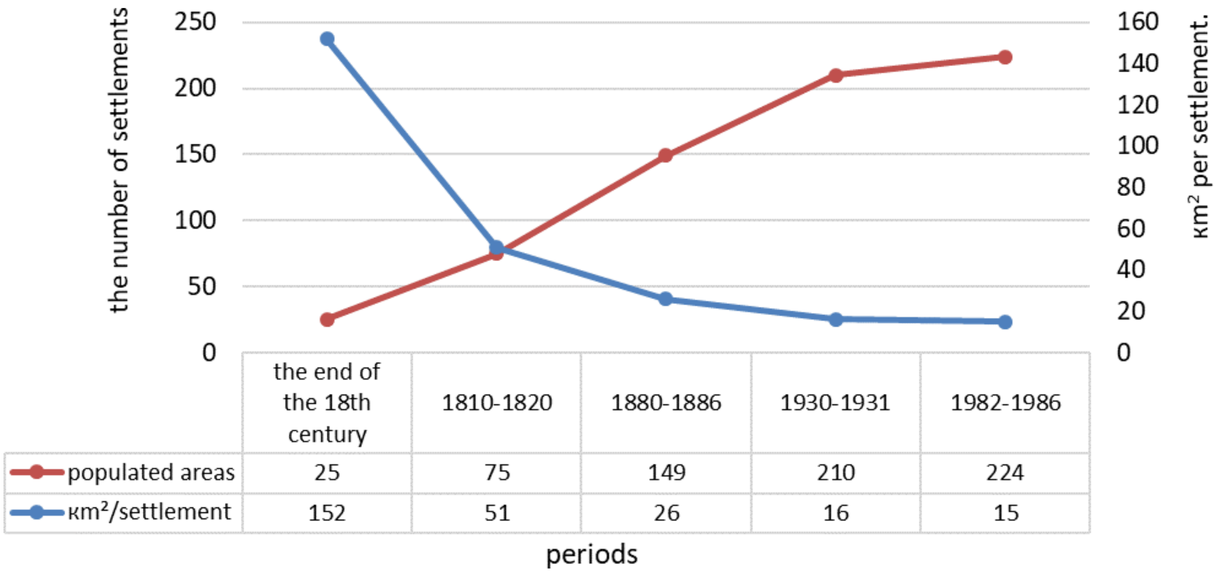


Figure 7. Changes in the number of settlements in Kryvyi Rih and the density of their location during the settlement of the territory.

We should remark that due to the lack of data on the population of Kryvyi Rih area at the end of the 18th century – the 1st half of XIX century, the calculations are based on the probable share of the population of 8 volosts, which later formed the Kryvorizky district. Thus, in 1785, the population was 1.7 thousand people [30]. The population of Kryvyi Rih area was presumably 1,671 people, according to the results of the calculation of the number of yards in the settlements of the region at the end of the 18th century (1780–1790). So, the indicators are correlated, which proves the reliability of the obtained calculations. At that time, the population density was 0.44 people per km^2 (figure 10).

At the beginning of the 19th century the number of settlements in Kryvyi Rih area increased

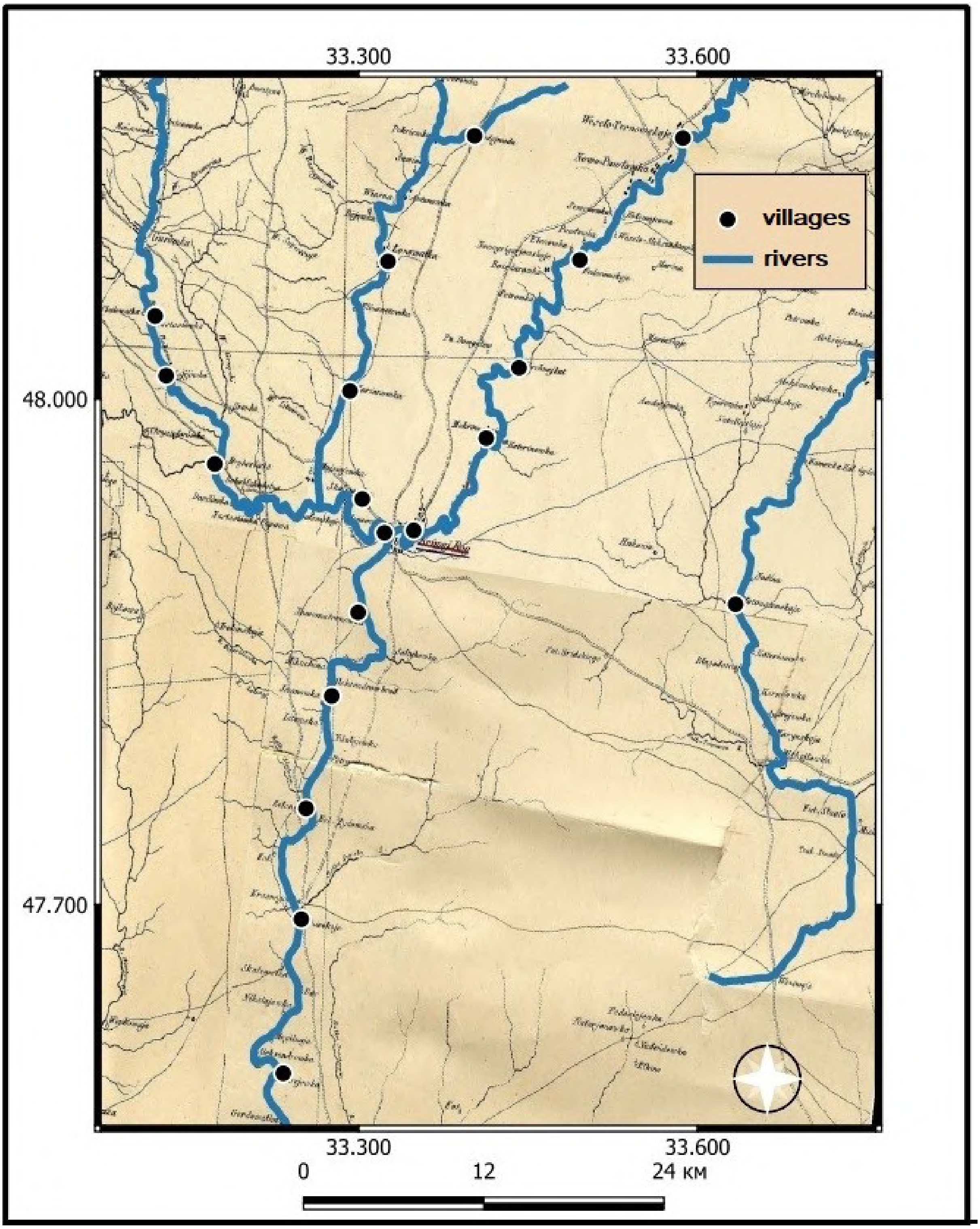


Figure 8. Localization of Kryvyi Rih settlements along riverbeds at the end of the 18th century (based on the Map of the Commonwealth of Nations).

almost threefold. According to the information provided on the Special Map of the Western Part of the Russian Empire by F. Schubert, the total number of settlements in the studied region

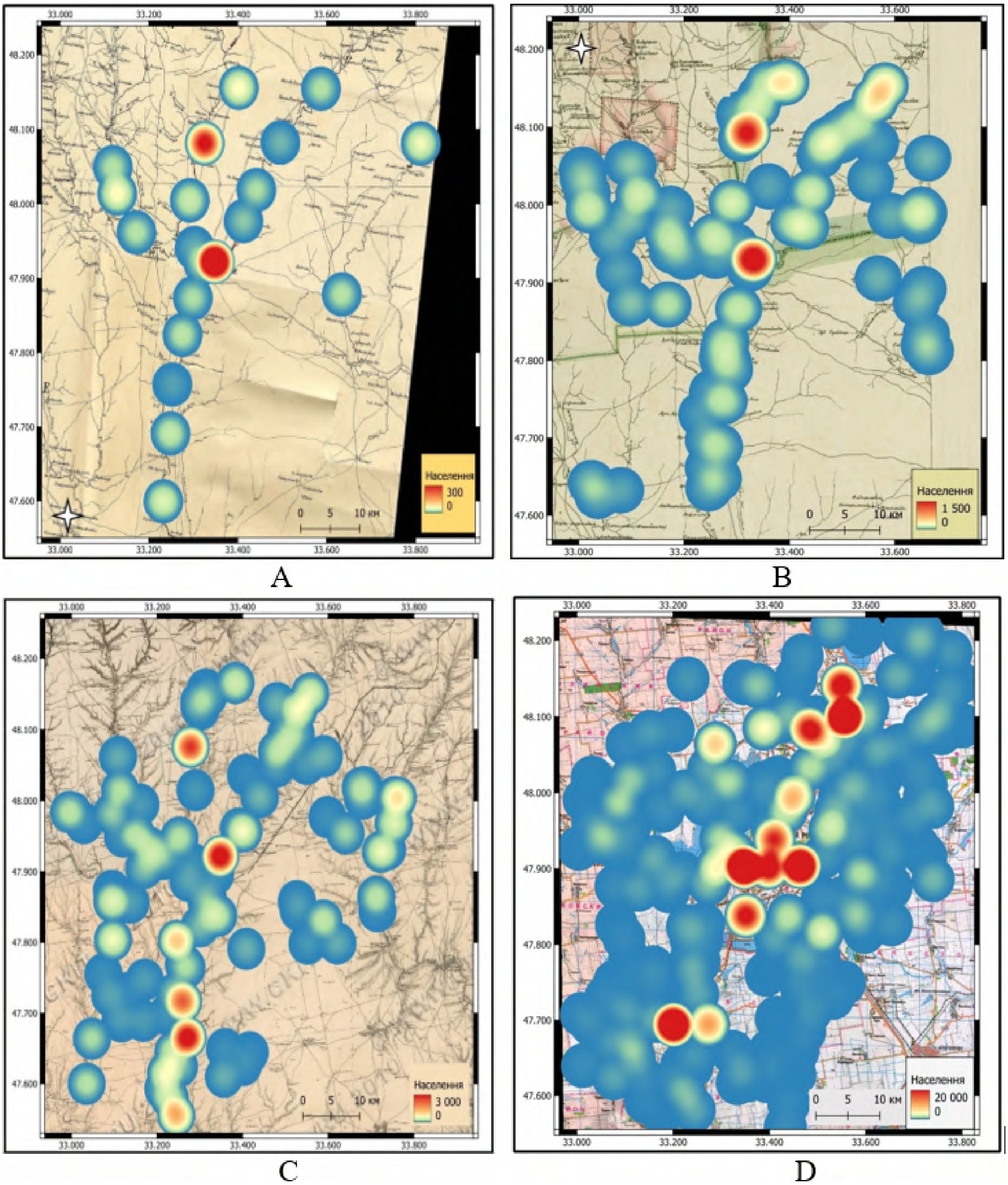


Figure 9. Heat maps of the population density of Kryvyi Rih in different historical periods of settlement of the region:*(A – Map of the Polish-Lithuanian Commonwealth; B – Special map of the Western part of the Russian Empire by F. Schubert; B – Updated three-mile Military Topographical Map of the Russian Empire; G – Map of the General Staff of the USSR Armed Forces).*

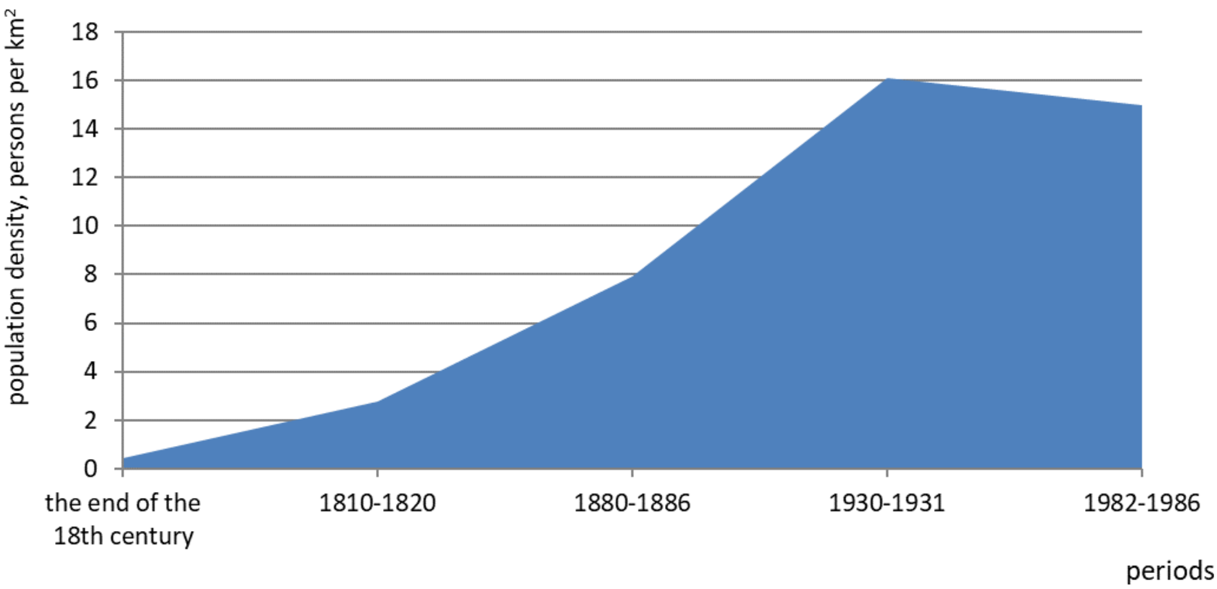


Figure 10. Dynamics of the population density of Kryvyi Rih area during the settlement of the territory.

was 75 (figure 7); the density is 1 settlement per 51 km^2 of the total territory, and the average distance between settlements is 4.1 km (figure 6).

The emergence of new settlements in the region is connected with the resettlement of a significant number of serfs from different parts of the Russian Empire, and is also the result of the anti-Semitic policy of the government of Alexander I, when Jews were expelled from Moscow, Petersburg and other cities. They founded the first Jewish agricultural colony of Ingulets. Later, their number grew to 7 [22].

The settlement structure of the region at that time almost did not change. New settlements gravitated to riverbeds of the Ingulets, the Saksagani, the Kamianka, and the Bokova, people also settled down near the Bokovenka and the Verbova rivers. Therefore, in Kryviy Rih area of that period there was a clear localization of settlements near the river valley landscapes.

The second focal factor together with the natural one that had a significant impact on the settlement of the population was the ethnic factor. Thus, certain systems of farming and land ownership specificity in Jewish colonies and their interrelation, contributed to the formation of some ethnonodes in the south and east of the region.

Overall, Kryvyi Rih territory at the beginning of the 19th century is characteristic of six areas with an increased density of settlements (figure 4B), the largest ones were the newly formed settlements along the Saksagan River in the north of the district (the settlements of Novo-Pavlovka, Bozhedarovka, Fedorovskoe, Semenovka), as well as in the south, along the Ingulets River (villages Aleksandrov Dar, Ivanovka, Nikolaevka, Petrovka, etc.). Here and further, the names of the settlements correspond to the names given on the historical maps.

At that time, the population of Kryvyi Rih also increased significantly: 10,455 people lived in the region. Generally, the spatial structure of quantitative indicators of population settlement has not changed. There remained two centers of development – the villages of Kryvyi Rih and Lozuvatka with a fairly even distribution of population density in the region (figure 9B). In the meantime, we can observe an increase in demographic indicators: 2,300 people lived in Kryvyi Rih, 1,590 in Lozuvatka. The average population in other villages increased to 90, and the population density was 2.75 people per km^2 (figure 10).

At the end of the 19th century the number of settlements in Kryvyi Rih area doubled to 149, and the density was 1 settlement per 26 km^2 of the total territory (figure 7). We can explain such an increase in the number of settlements due to their location on vacant land between previously built settlements (figure 4C). It resulted in a transition from a linear structure of settlement of the region to a linear-planar one, increasing the average distance between settlements to 4.9 km compared to the indicators of 1810–1820 (4.1 km) (figure 6).

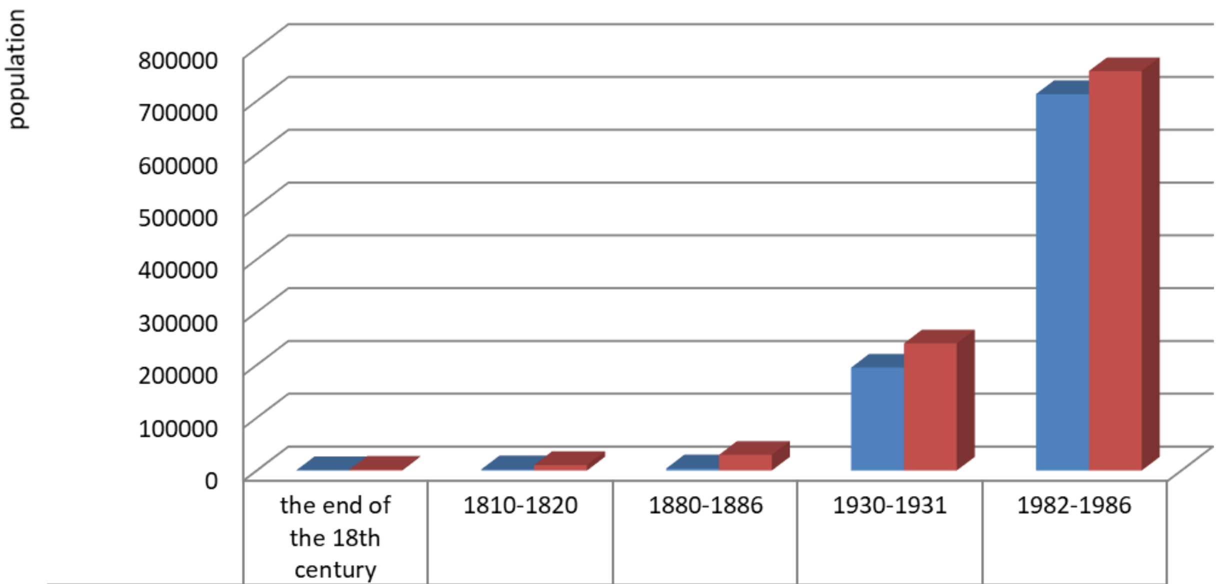
The increase in the number of settlements on vacant land led to a more uniform structure of their density (figure 9C). We note only two areas with a higher concentration: one in the center of the region (near Kryvyi Rih), the other in the west (in the meanders of the Bokovenka river). The concentration of settlements Vladimirovka, Popovka, Khrushchevka, Bohoblagodatnaya and others in the meanders of the Bokovenka river is connected with the fertility of the land and proximity to water. Yet, an economic core was gradually forming around Kryvyi Rih.

From the middle of the 19th century Kryvyi Rih turned into a significant agricultural and trade center of Southern Ukraine, which made it a town of the Kherson province in 1860 [25]. Since then, the development of Kryvyi Rih was affected by its growing economic role. The rapid socio-economic development of the region impacted the population growth. So, 3,644 people lived in Kryvyi Rih in 1859; 4,023 people in 1880; 15,859 people in 1890, and at the end of the 19th century 35,000 people already lived on the territory that is part of the city nowadays [18]. The reason for such a dramatic Kryvyi Rih population increase was the discovery of large reserves of iron ore in Kryvyi Rih, and hard coal in Donbas, which created the prerequisites for the development of a metallurgical base. In 1897 the Kryvyi Rih iron ore district placed first in ore extraction in the Russian Empire, and in 1900, 79 mines operated there. Thus, Kryvyi Rih became a powerful labor market, which caused mechanical movement of the population to the city from its outskirts and nearby settlements. The construction of the Catherine railway in 1884 boosted the development of Kryvyi Rih as well, connecting the city with the industrial regions of Dnipro and Donbass [22].

The transformation of Kryvyi Rih into a big economic center entirely effected the location and functioning of virtually all settlements of Kryvyi Rih area. Firstly, the territorial organization of the population changed: a set of processes or actions that regulate the interrelation between the population location and production, interconnection and subordination. The changes in the nature of settlement near Kryvyi Rih after the construction of the Hdantsivka ironworks in 1890–1892 can serve as an example. Peasants from nearby settlements were used to work at the plant. Consequently, at the end of the 19th century Hdantsivka absorbed several small settlements: Katerynivka, Likhman's farm, Tychy Prytulok, Tsareva Mogyla, and others [23]. Most of the mines were opened on the lands of landowners or leased lands of peasants. Thus, the Galkovsky (Artema) mine was opened in 1888 on the lands of the Galkovsky landowners, the Rostkovsky mine was founded in 1886 – on the land of the landlady M. Rostkovskaya, the Veseloivanivskyi mine was founded in 1898 on the leased lands of Veseloivanivka villagers, the Boyky mine was founded in 1899 on the agricultural lands of Kryvyi Rih villagers.

In general, in 1880–1886, the population of Kryvyi Rih area made up almost 30,000 inhabitants (figure 11). Compared to the beginning of the 19th century, the third population center in the south of the region (the colony of Ingulets and the village of Shiroke) came into being making the main changes in the spatial structure of quantitative indicators of population displacement (figure 9C). If we do not count the population of these settlements, the average resident number of other settlements of the region increased to 118, and the population density was 7.8 people per one km^2 (figure 10).

It is worth noting that the rural settlement network significantly changed its role in the general system of settlement of the region, since at that time it acquired a secondary role in the economic development of Kryvyi Rih area, which consequently altered its functions and ecological-reproductive load. Virtually, a gradual transition from natural to economic factors of settlement structure formation took place at that time.



	the end of the 18th century	1810-1820	1880-1886	1930-1931	1982-1986
Kryvyi Rih	762	2300	4023	195000	713059
Kryvyi Rih area	1671	10455	29789	240800	756559

Figure 11. Changes in the population in Kryvyi Rih and Kryvyi Rih area in different periods of settlement.

The analyses of the nature of settlement of Kryvyi Rih area in the period between the beginning of the 20th century and before the Second World War is challenging as there is almost no necessary factual material. We can explain the lack of high-quality cartographic materials of that period by the changes in the administration of the region (Kryvorizka Volost, Kryvorizka County, Kryvorizka District), the low level of population accounting by settlements, especially after the Bolsheviks seized power in 1917.

Therefore, we analyze the Map of the German Army to study the nature of resettlement in Kryvyi Rih area not taking into account the spatial indicators of the population. Population data are correlated since 1930.

Factually, the settlement structure of the Kryvyi Rih settlements was finally formed by that time. The active process of resettlement of peasants during the period of the Stolypin reform (1906), and mostly the abolition of landlord land ownership by the Decree on Land (November 8, 1917) with the subsequent distribution of allotments among peasants, contributed to the active development of almost the entire territory of the region.

By 1930 the number of settlements had increased to 210 making a fairly uniform planar structure of settlement in the region (figure 4D). The density of settlements was 1 settlement per 16 km^2, the average distance between settlements decreased to 3.9 km. The total population of Kryvyi Rih at that time was 240,800 people, of which 195,000 lived in Kryvyi Rih. Excluding the population of Kryvyi Rih, Lozuvatka, and Shiroki, the average number of inhabitants of the villages increased to 199 people, and the population density was 16 people per km^2 (figure 10).

According to the Map of the General Staff of the USSR Armed Forces, the number of settlements (224) in Kryvyi Rih area in 1982–1986 hardly changed compared to 210 in 1930. However, judging by historical materials two mutually opposite processes in the settlement of the region occurred in that period: a significant increase in the number of settlements until the middle of the 20th century, which later began to decrease. The gradual increase in the number of settlements is quite understandable: Kryvyi Rih area has fertile soils and a favorable geographical position combined with the irrigation system in the region which contributes to the development of a rural settlement network.

The process of physical disappearance of settlements in the region was partially noted even before the Second World War. The settlements Karachunivka, Moiseivka, Khrushchevka, Bogoblagodatne, Hannivka vanished as they fell into the zone of flooding by the Karachuniv reservoir (works on the construction of the Karachuniv dam began in 1932). Similar processes occurred during the creation of the Iskrivskyi, Kresivskyi, Southern and other reservoirs. However, settlements faded away more massively in the 1970s. If we analyze the graph of changes in the number of settlements in Kryvyi Rih area (figure 7), we can say that at certain times their number reached 240–250 settlements. The decrease in the number of settlements during the growth of urban agglomeration is a fairly common trend throughout the post-Soviet space, which is due to a number of reasons.

Firstly, Kryvyi Rih absorbed nearby settlements. Thus, in 1960–1970, the city of Ingulets, the villages of Rakhmanivka, Zaliznychne, Suvorovo, Kalinina, Zelene, Terny, R. Luxemburg, Novoivanivka, Gleyevatka, etc. were subordinated to the Kryvyi Rih City Council [25]. Therefore, the city of Kryvyi Rih is an agglomeration created by separate villages and working villages built near the facilities of the metallurgical industry (mines and factories). The city territory is a united industrial landscape and urban development complex; which shape follows the configuration of the Kryvyi Rih geological structure with iron ore deposits.

Secondly, the rural population outflew significantly to Kryvyi Rih. The lack of employment in villages distant from the economic core of Kryvyi Rih causes their disappearance (for example, the village of Kateryno-Natalivka, which actually does not exist nowadays).

Thirdly, the villages are administratively cancelled because of their ineffectiveness or location in the zone of potential risk. For example, the village of Shyroke was divided into two villages: Hryhorivka (Grygoro-Hrygorivka) and Shyroke until 1934; due to the construction of the Dnipro-Kryvyi Rih canal, residents from the surrounding villages of Hrushivka, Kuta, and Maryanskoye were resettled in the village of Pershe Maia (name on the map).

The settlement structure of Kryvyi Rih remained unchanged for a long time: evenly planar (figure 5) (with the density of 1 settlement on average – per 15 km^2, the average distance between settlements is 3.8 km).

The total population of Kryvyi Rih area in the period 1982–1986 increased significantly (756,559 people), which is caused by a dramatic increase in the population of Kryvyi Rih city (up to 713,059 people). The number of the rural population simultaneously decreased by 2,300 people (up to 43,500) compared to 1930. The population density consequently decreased to 15.1 people per km^2 (figure 10).

We display the identified trend of changes in the quantitative composition of the population of the region in the structure of the heat map of the population density of Kryvyi Rih area of the specified period (figure 9D). The map demonstrates that the linear zone of the city territory stands out clearly as the area of maximum population density among the low indicators of the rural settlement network emphasizing the role of Kryvyi Rih as the economic core of this region. Due to the specificity of the urban planning structure of Kryvyi Rih, the quantitative indicators of the population are displayed in the form of indicators of its individual components (former villages, towns, working villages, and micro districts)

After the analysis of changes in the population of the "cross-cutting" settlements of the region (figure 12), we divide them into three groups according to the dynamics of changes:

- the first group is characterized by a sharp increase in the number of the population in the second half of 20th century (histograms with clear distinct right-sided asymmetry): the city of Kryvyi Rih, the town of Radushnoe, the villages of Stepove, Poltavka, etc., as well as settlements located near Kryvyi Rih, which are under its high economic influence;

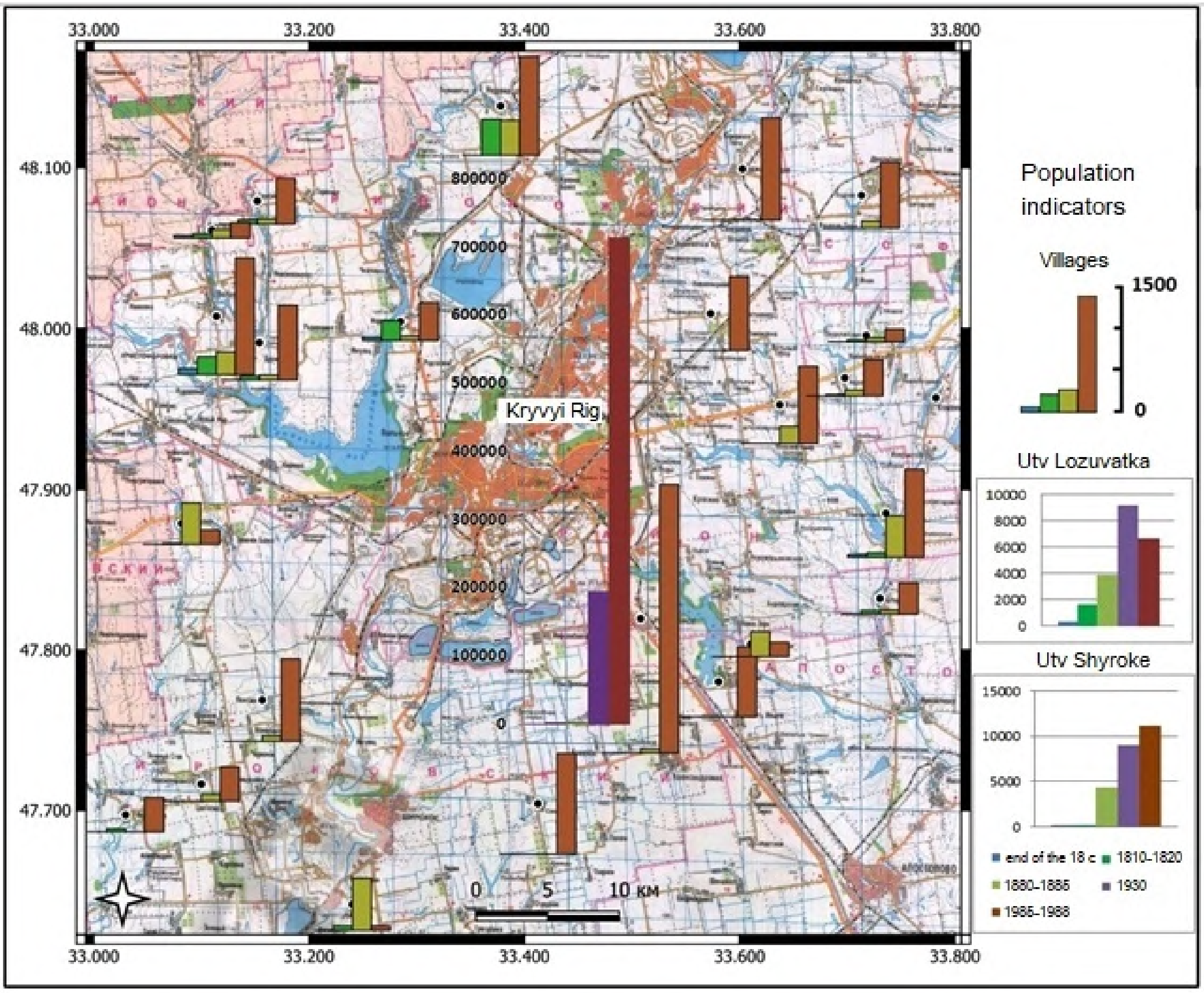


Figure 12. Histograms of changes in the population of "cross-cutting" settlements of Kryvyi Rih (histograms of the city of Kryvyi Rih, Shiroke township and Lozuvatka township are built on separate scales).

- the second group illustrates the regular statistical distribution of the population indicator (histograms with bilateral asymmetry): Shirokoye township, Novokurske, Novo-Kovno, Makarovka and others. These settlements are characterized by regressive processes in the population size. These settlements mostly used to be Jewish agricultural colonies or were under their economic influence before the Second World War;
- the third group comprises settlements with a stable dynamic development of demographic indicators (histograms with smooth right-sided asymmetry). This includes the villages of Valovoye, Anastasovka, Zlatoustovka, etc., which are distant from Kryvyi Rih, so the city economic influence is insignificant.

4. Conclusion

The retrospective analysis of the territorial organization of the settlement of Kryvyi Rih area leads to the following conclusions:

1) the model of the territorial organization of the Kryvyi Rih settlement process was formed during the historical resettlement of the population in the region and is determined by the

spatio-temporal changes of the following indicators: the nature and number of settlements, settlement size, number and density of the population, the ratio of the rural and urban population, etc.;

2) a methodology for retrospective modeling of the historical settlement of Kryvyi Rih area is developed using historical topographic maps and adopting GIS;
3) natural factors, particularly the dominance of the location of the river network in the area, were the main factors in the formation of the original settlement structure of Kryvyi Rih area from the beginning of settlement to the end of the 19th century;
4) the resettlement of the population in Kryvyi Rih during the 19th century was also determined by the ethnic factor connected with the advert and development of Jewish agricultural colonies. The farming systems and peculiarities of land ownership in Jewish colonies caused the formation of separate ethnonodes in the south and east of the region;
5) the settlement of Kryvyi Rih area witnessed a transition from a linear (in the middle of the 19th century) settlement structure of the region to a linear-planar (at the beginning of the 20th century) and planar (in the 30s of the 20th century);
6) the end of the 19th century is marked by a change in the role of the rural settlement network in the general settlement system of the region caused by a gradual transition from natural factors of settlement structure formation to economic ones; at the beginning of the 20th century Kryvyi Rih becomes the economic core of the region development;
7) the analysis of temporal changes in the number of the population of "cross-cutting" settlements of the region prompts their division into three groups depending on the dynamics of changes and Kryvyi Rih economic effect on their development;
8) the findings of study are indicators of population settlement in different time periods of the development of the region: the number of people in settlements; population density in the region; average distance between settlements, etc.; these indicators present a significant contribution to the historical and geographical research of the region.

We envision the prospects for further research in the retrospective study of changes in the natural landscapes of Kryvyi Rih.

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Geography of the COVID-19 pandemic in Ukraine and the world: similarities and differences

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Abstract. The COVID-19 pandemic has its own geography, reflected in the spatio-temporal model of its regional evolution, with uneven and spatially differentiated worldwide spread. The global nature of the coronavirus pandemic makes it impossible to study its evolution in a single country in isolation from global realities. Comparison of the dynamics of growth in the number of detected cases of coronavirus infection in the world and Ukraine shows that the pandemic is wave-like, but the amplitude, period and length of the variations barely match. Each of the waves of the pandemic in the world and Ukraine had its own characteristics in the spatial and temporal differentiation of the disease parameters, which was determined by various and multidirectional factors. Based on the results of the geospatial analysis, a zoogeographical map of Ukraine's zoning according to the epidemiological course of the COVID-19 pandemic was constructed, which reflects the spatial differentiation of the pandemic parameters, which is associated with various and multidirectional factors that determine the course of the epidemic, the main ones being: population density and spatial mobility, as well as the peculiarities of regional governance.

1. Introduction

The COVID-19 pandemic will go down in the history of humanity as one of the most important events of the first quarter of the 21st century [1]. It has caused unprecedented consequences in the political and socio-economic spheres of all countries of the world without exception [2, 3]. Thus, according to the WHO, the total number of deaths in the world directly or indirectly related to the COVID-19 pandemic (excess mortality) amounted to at least 20 million people, and the IMF estimated the global economic losses since the beginning of the COVID-19 pandemic at $3.7 trillion.

As a result, the scientific community is widely interested in addressing all aspects of the pandemic [4–6]. Researchers and geographers do not stand aside. While epidemiologists, virologists, and physicians were developing drugs, vaccines, and medical solutions, geographers around the world were studying the relationship between the pandemic outbreak and geographic space. This was facilitated by the availability of various geospatial analysis techniques using GIS to map and monitor the spread of various diseases, including infectious ones [7–11].

The beginning of research in this area is associated with the creation of various online and mobile GIS and mapping dashboards and applications (e.g: *Johns Hopkins University Center for Systems Science and Engineering dashboard; World Health Organization dashboard; HealthMap: analyzing and mapping unofficial sources on the Internet*, etc.) to track the coronavirus epidemic. Some of these dashboards and apps received near real-time data updates [12]. Communication through dashboards based on interactive maps provided unlimited access to information about the spread of the virus both globally and in specific regions and metropolitan areas. At this stage, online dashboards were an important source of information, but GIS methods were more focused on visualizing the development of the COVID pandemic.

After the spread of the pandemic, which provided a statistical sample, studies using geospatial analysis methods appeared. As rightly noted by Helbich, Mute Browning and Kwan [13], the use of geographical principles related to spatial and temporal units of analysis helps to make fruitful progress in COVID-19 research. Technically, geospatial methods for analyzing the spread of diseases are classified into three categories: disease mapping, exposure mapping, and spatial epidemiological modeling [14]. Research on the spread of COVID-19 has been conducted in all of these areas [12, 15–17].

The most common spatial methods used were clustering, hotspot analysis, spatio-temporal scan statistics, and regression modeling. The researchers used a wide range of spatial and statistical software.

It is important to note that the various geospatial methods used by researchers (e.g., spatial autocorrelation [18], or spatio-temporal autocorrelation [19], etc.) aim to explain the dynamics of the pandemic and develop a scientific forecast of its spread. Spatio-temporal mapping of confirmed cases is correlated with geographic factors such as climate, population density, population composition, travel patterns, and others.

For example, Helbich, Mute Browning and Kwan [13] found that COVID-19 is positively correlated with temperature and humidity, but also that these factors alone are not sufficient to predict infection rates. A study by Briz-Redón and Serrano-Aroca [20] demonstrated a high spatial correlation (+0.85) between population density and infection rates, while Sannigrahi et al. [21] added that, in addition to population size, income (-0.68) and poverty (+0.69) have a high correlation with infection rates. In general, GIS technologies have demonstrated high efficiency in creating geoforecasts of the pandemic spread [11, 15].

In addition to global studies, most countries affected by the pandemic have conducted research on the spread of the disease at the regional level. It should be noted that most of the published studies focus on the countries most affected by COVID-19: China [22, 23], North Korea [18]; the United States [24, 25], Brazil [26–28], Italy [29–31], Spain [20], Portugal [32], Germany [10], etc. Most spatial epidemiological studies were conducted during the first months of the epidemic. This made it possible to identify the factors influencing the spread of the pandemic at the regional level and to predict the epicenters of the disease in the near future.

Geospatial studies of COVID-19 in Ukraine are rather limited. As in global research, studies of the spread of the coronavirus began with the creation of interactive maps. Thus, with the increase in the number of confirmed cases, *the Main Situation Center of Ukraine* (under the National Security and Defense Council of Ukraine) created an electronic map of the spread of COVID-19 infection in the world and in Ukraine. The map was updated daily with statistics on laboratory-confirmed cases; the number of patients; the number of recovered patients; the number of deaths, etc.

Experts of the World Data Center for Geoinformatics and Sustainable Development created an interactive thematic panel *WDC-Ukraine COVID-19 Dashboard* to track and forecast the spread of COVID-19 in Ukraine. The service provided data for Ukraine as a whole and by region on the number of laboratory-confirmed COVID-19 cases, deaths, and recovered patients. The information was presented in the form of maps, charts, and counters.

The aforementioned studies are limited to the geospatial analysis of the spread of COVID-19 in Ukraine. As an exception, there are some works in which the authors demonstrate cartographic materials on the pandemic. Most studies of COVID-19 in Ukraine are related to the impact of the pandemic on various aspects of the country's socio-economic life: the crime situation [33], the labor market [34], the economy [35], etc.

Thus, there is no doubt that geoinformation monitoring of the COVID-19 pandemic is a unique tool for studying the peculiarities of the spatial development of the disease, which provides the scientific community and practitioners with a wide range of benefits. Its use allows developing territorial forecast models of the pandemic, creating various medical and cartographic materials (maps of epidemiological burden, medical and geographic forecast, epidemic foci, etc.)

Such research should be conducted at all regional levels, so studying the geography of the coronavirus pandemic in Ukraine is a relevant and crucial task. However, given the fact that the global nature of the COVID-19 pandemic makes it impossible to study its development in a single country apart from global realities. The purpose of the research is to conduct a geospatial analysis of the spread of COVID-19 in Ukraine and the world, identifying similarities and differences.

2. Methods

The work is based on the synthesis of monitoring and geoinformation approaches to the study of the new coronavirus infection. The main parameters of geoinformation monitoring include a variety of data sources and visualization of the dynamics of the processes under study. The statistical basis of the study is the materials from the official websites of global and Ukrainian organizations: World Health Organization, Johns Hopkins University, UNICEF, Ministry of Health of Ukraine, etc.

The Quantum GIS geoinformation application was used as a geoinformation platform. The geospatial analysis was carried out using the methods of cartodiagrams and choropleths with the number of quintile classifications according to the number of research objects. The network analysis was based on the interpolation of spatial-attribute data using the inverse distance weighting (IDW) method.

3. Results and discussion

The COVID-19 coronavirus pandemic has been going on for over three years. During this time, it has spread to almost all countries of the world, with more than 765 million cases of infection recorded, according to official data, and the disease has taken millions of lives, leading to a global economic recession and other crisis phenomena in the socio-economic life of our planet.

COVID-19 was first reported in December 2019 in Wuhan, China, and has spread around the world. It is caused by the SARS-CoV-2 virus, a coronavirus discovered in 2019. The rapid spread of the virus from Wuhan around the world is attributed to the city's well-established air links with almost all continents, but primarily with Asian countries. Thus, in early January 2020, the virus spread to Asia's neighboring countries: Japan, South Korea, Taiwan, Thailand, and Vietnam. As soon as the virus entered these countries through the airline network, it began to spread exponentially from these territories and by the end of January it had reached the United States, Germany, Russia, France, Canada, Italy, and Spain. These are the countries that had the largest number of business, trade, and transportation contacts with China and with each other.

Thus, in the first month of 2020, COVID-19 was detected in 26 countries, and in February – in another 36 countries in Southwest Asia and Latin America In March, the pandemic already

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covered 150 countries, and by early April – almost the entire world. According to WHO, the number of confirmed cases has exceeded one million.

In Ukraine, the first case of COVID-19 coronavirus infection was confirmed on March 3, 2020. The patient arrived in Chernivtsi from Italy, where he had been traveling from February 21 to 26. Later, cases of infection were detected in Khmelnytskyi, Odesa, Donetsk, Kharkiv, Zaporizhia, Kherson, and Vinnytsia regions.

Epidemiologists call the first patients people who returned from foreign trips, where they could have caught COVID-19. For example, patients in the eastern regions returned from Egypt and Europe, particularly France. In the western regions – from Austria, Hungary, and Italy. In the southern regions - from the United Arab Emirates, Egypt, the United States, and European countries (figure 1). Due to personal contacts with infected people, COVID-19, as a respiratory disease, spread rapidly across the country.

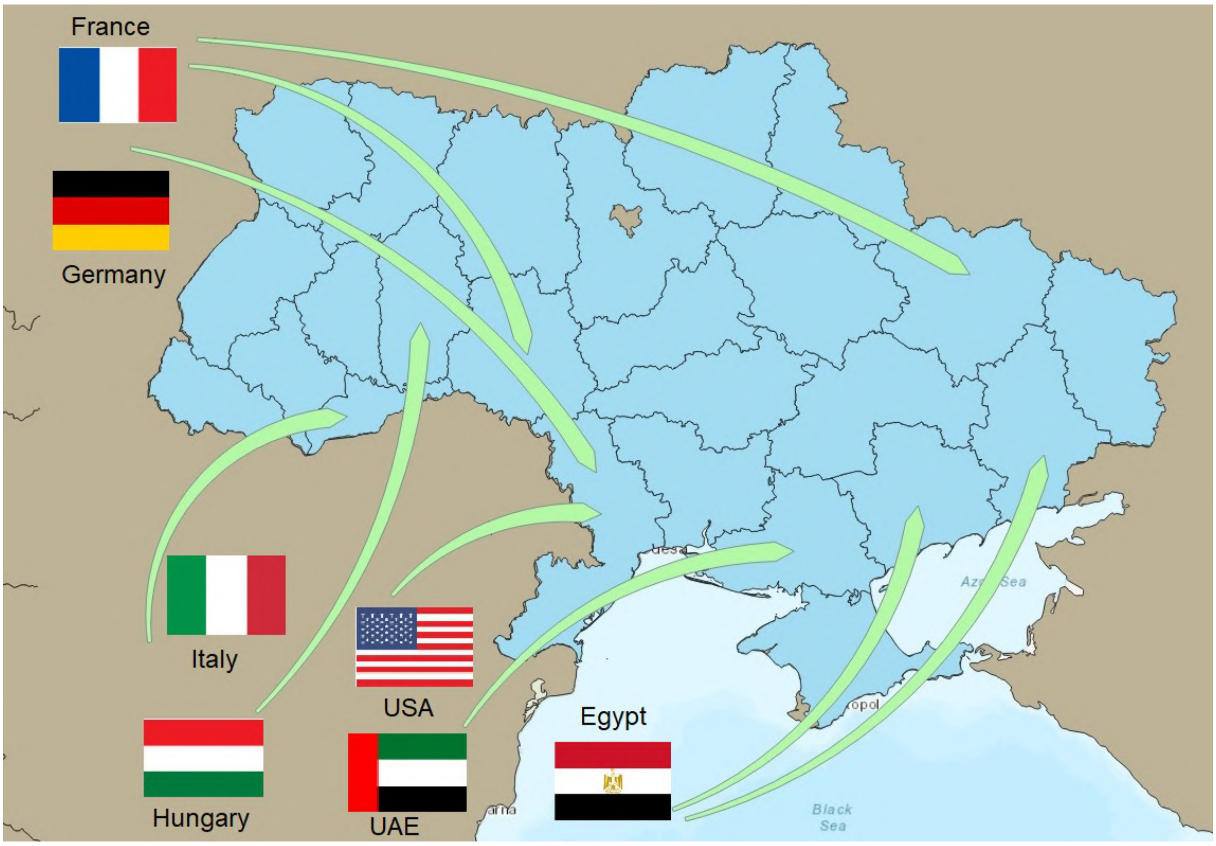

Figure 1. The geography of the first cases of COVID-19 in Ukraine.

Thus, the mechanism of the virus infection in Ukraine is similar to the global one – from the primary source through the chain of contacts with the infected. However, due to the lack of direct flights to Wuhan (China), Ukraine "received" the virus after its long transit through other countries almost two months later than countries in Asia, Europe, and America.

This temporal discrepancy has been observed throughout the pandemic. This conclusion is best illustrated in figure 2, which shows the temporal correlation between the waves of disease development in the world and Ukraine.

From this graph, we can identify four waves in the development of the disease both globally and in Ukraine. The first wave of pandemics was the longest, with a global start in July 2020 and an end in February 2021, with a peak in December 2020-January 2021. In Ukraine, this

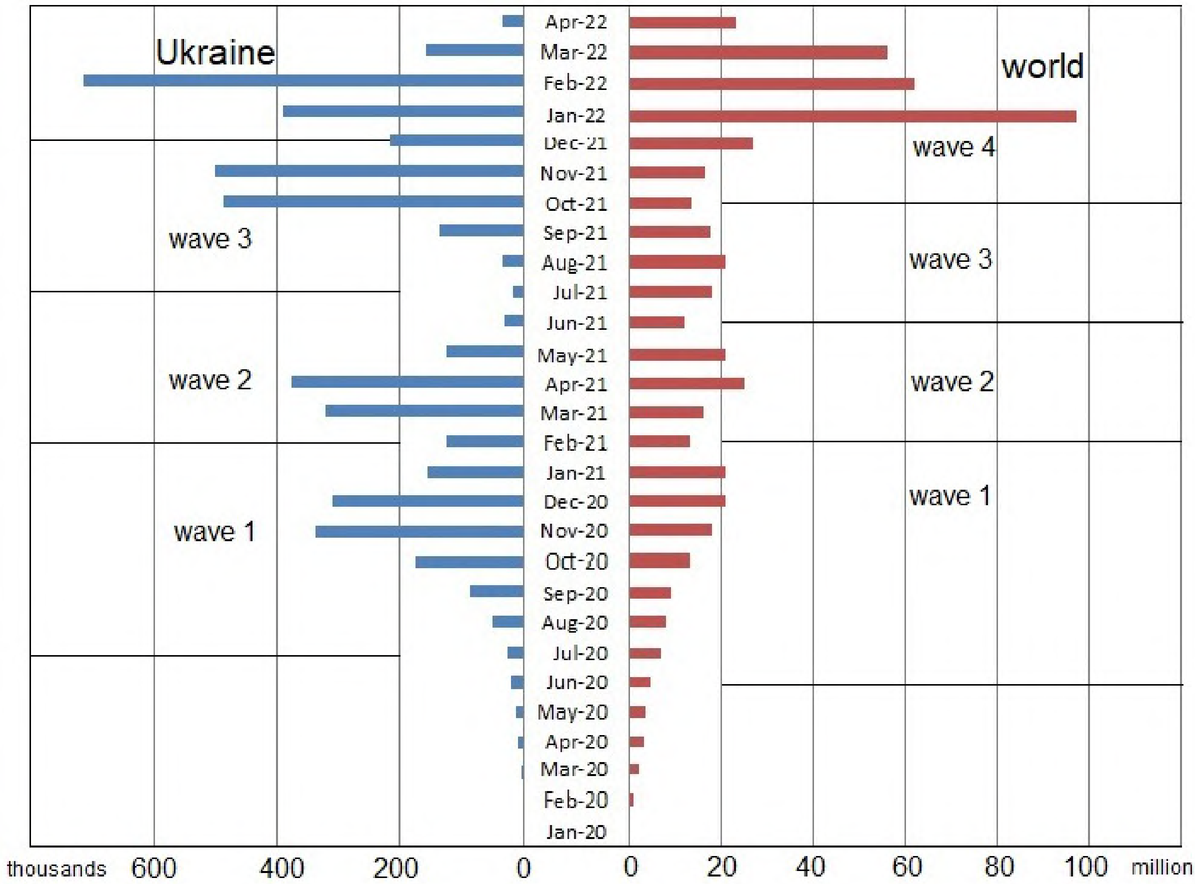

Figure 2. The epidemiological profile of COVID-19 during the pandemic in Ukraine and the world.

wave began one month late (July 2020), but due to the active spread of the virus across the country, the peak of the disease was observed a month earlier – in November 2020.

An analysis of choropleth maps of the spread of coronavirus in the world has revealed that the largest number of COVID-19 cases at the beginning of the first wave occurred in countries located in the subtropical monsoon climate belt and its northern bands. These are: Turkey (165 thousand cases), Iran (155 thousand), Italy (233 thousand), Spain (240 thousand), etc. It can be concluded that at the early stage of the pandemic, the climatic factor (high temperature and humidity) created a favorable basis for the spread of the pandemic, which was exacerbated by the development of tourist flows in these regions.

At the peak of the first wave, the epicenter of the disease shifted from East Asia to North America and Western Europe. As a result, the countries with the largest populations in this belt are already leaders in terms of the number of infections: The United States (26.5 million), Brazil (9.2 million), France (3.2 million), and India (1.4 million). Thus, population density is still a major factor in the pandemic.

It is important to note that while at the beginning of the first wave in Europe, mainly Western and Central European countries and, in particular, megacities were affected, later on, the epicenter shifted to Eastern Europe.

Due to the long period of the pandemic as well as the lack of sufficient vaccines, when the total number of confirmed cases worldwide was nearly 117 million, the first wave had the highest number of deaths at 2.66 million [36].

The lack of a vaccine, as well as the ineffectiveness of the lockdown, contributed to the active spread of coronavirus in Ukraine. Thus, while at the end of April 2020, about 10 thousand people were infected in the country, by the end of November, more than 700 thousand cases were recorded, of which more than 12,000 died (mortality rate of 1.7%). The average daily number of infected people was 12 thousand, with 250 deaths.

By region, the total number of cases during the peak period ranged from 5,500 in Kirovohrad region to more than 56,000 in Kharkiv region (as of 11/28/20). The highest infection rates were observed in the most populated regions: Odesa (47 thousand), Dnipro (40 thousand), Kyiv (39 thousand) regions, etc. At the same time, most (80%) of the detected cases of infection were recorded in the megacities of these regions.

Nevertheless, it is worth noting the higher than average rates in the western sparsely populated regions: Rivne (31 thousand), Chernivtsi (34 thousand), Ivano-Frankivsk (38 thousand), etc. In the diagram of the relationship between population and the number of coronavirus cases in the regions of Ukraine during the first wave of the pandemic (figure 3), the western regions are localized separately, demonstrating the absence of such a relationship. This indicates that in the early stages of the pandemic in Ukraine, the carriers of the coronavirus – Ukrainian workers from European countries – played a major role in the spread of the coronavirus, who began arriving end masse in the western regions of the country after the announcement of lockdowns in Europe. The deviation from the general trends in two regions – Donetsk and Luhansk – is noteworthy. This can be explained by the lack of correct data on the population of the regions after Russia annexed parts of these regions in 2014.

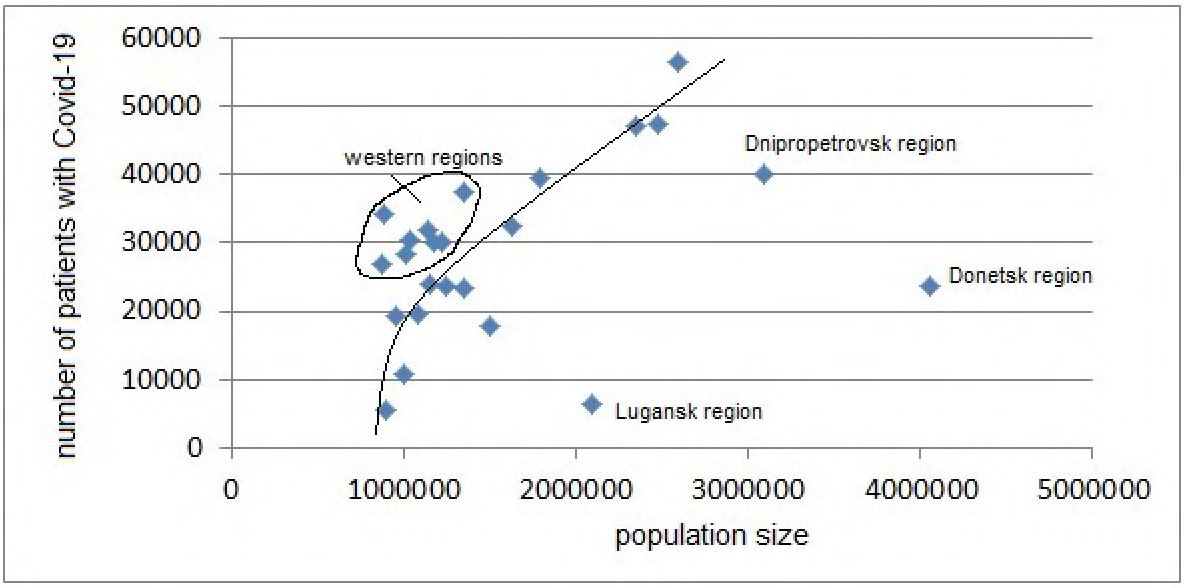

Figure 3. The relationship between the number of population and the number of diseases caused by coronavirus infection in the regions of Ukraine during the first wave of the pandemic.

Similar trends in the beginning of the epidemic were established during geospatial studies of the H1N1 influenza pandemic in Ukraine in October-December 2009 [35]. The western regions of the country also played the role of centers of disease spread.

The second global wave of the pandemic was observed from March 2021 to June 2021, with a peak in April 2021 (figure 2). It was caused by the emergence of a new coronavirus mutation, the beta strain, which was called the British strain. As of mid-May 2021, 163 million cases of coronavirus infection were reported worldwide. The British strain first affected European countries and then spread to North and South America.

At this stage of the pandemic, a general model of spatial differentiation of the spread of the COVID-19 virus in the world was formed, which remained until the end of the pandemic (figure 4). Therefore, the choropleth maps of the spread of coronavirus in the world, based on the indicators of subsequent waves of pandemics, do not differ significantly. The only difference was in the absolute number of people infected: it increased significantly from one wave to the next.

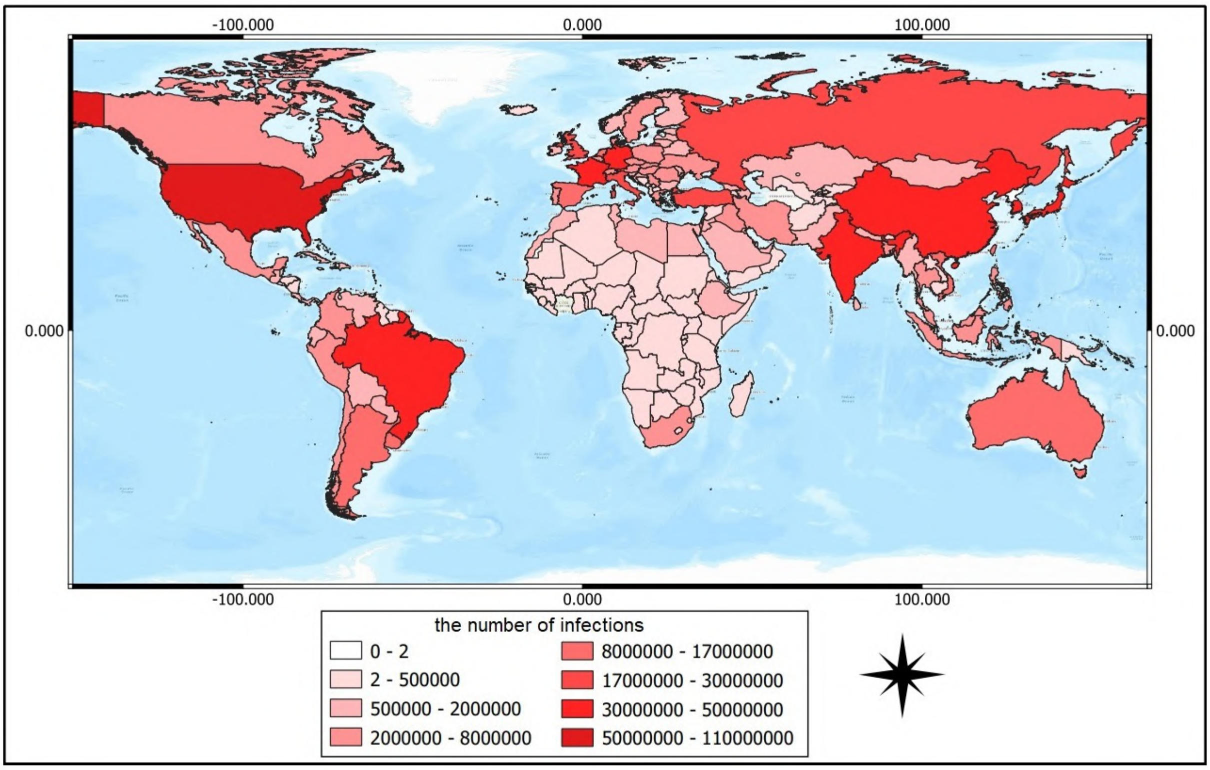

Figure 4. Horopleth map of the distribution of the number of detected cases of COVID-19 infection in the world at the end of the pandemic (data as of March 9, 2023).

As a result, the United States (33 million), India (30 million), and Brazil (18 million) remained the leaders in the number of COVID-19 cases, but the number of cases in Europe increased rapidly: France (5.6 million), Turkey (5.3 million), the United Kingdom (4.5 million), and Italy (4.2 million). In total, almost 47 million confirmed cases of infection were recorded in Europe during the peak of the second wave, despite the strict measures taken by the governments of these countries to contain the spread of the pandemic.

In total, during the second wave, almost 70 million confirmed cases were identified worldwide, with 1.33 million deaths [8].

The second wave of the pandemic in Ukraine was almost synchronized with the global one: it started in March 2021, ended in July 2021, and peaked in April 2021. It was more powerful than the first one, both in terms of the number of cases and the number of deaths.

During the second wave, almost 1 million people were infected in Ukraine, and during its peak period, two million people were infected, with more than 16 thousand daily laboratory-confirmed cases. Up to 400 people died of coronavirus every day in the country.

Such an exponential increase in the number of new infections during the second wave is due to the delay in the vaccination campaign compared to most European countries and its very slow pace. Vaccination became widespread in Ukraine only in late summer 2021. As a result of the diffusion of the virus during the second wave, the top five regions in terms of the number of cases were formed (as of May 1, 21): Kharkiv (137103), Odesa (134410), Lviv (130217), Dnipro (122704), and Kyiv (119241) regions. In fact, their "leadership" remained until the end of the pandemic (figure 5).

This is explained by the largest population of the respective regions and large metropolitan areas. High population density, as an indirect indicator of social contacts, was the main factor in the spatial differentiation of pandemic indicators at this stage.

The lowest number of infected persons was recorded in (data as of May 1, 21): Kirovohrad (18489), Luhansk (23644), and Kherson (31498) regions, which are the regions farthest from the disease centers and have low population density.

The third global wave of pandemic lasted from the beginning of July 2021 and ended in October 2022 (peak in August 2021). Researchers attribute it to the emergence of a new strain of coronavirus, Delta.

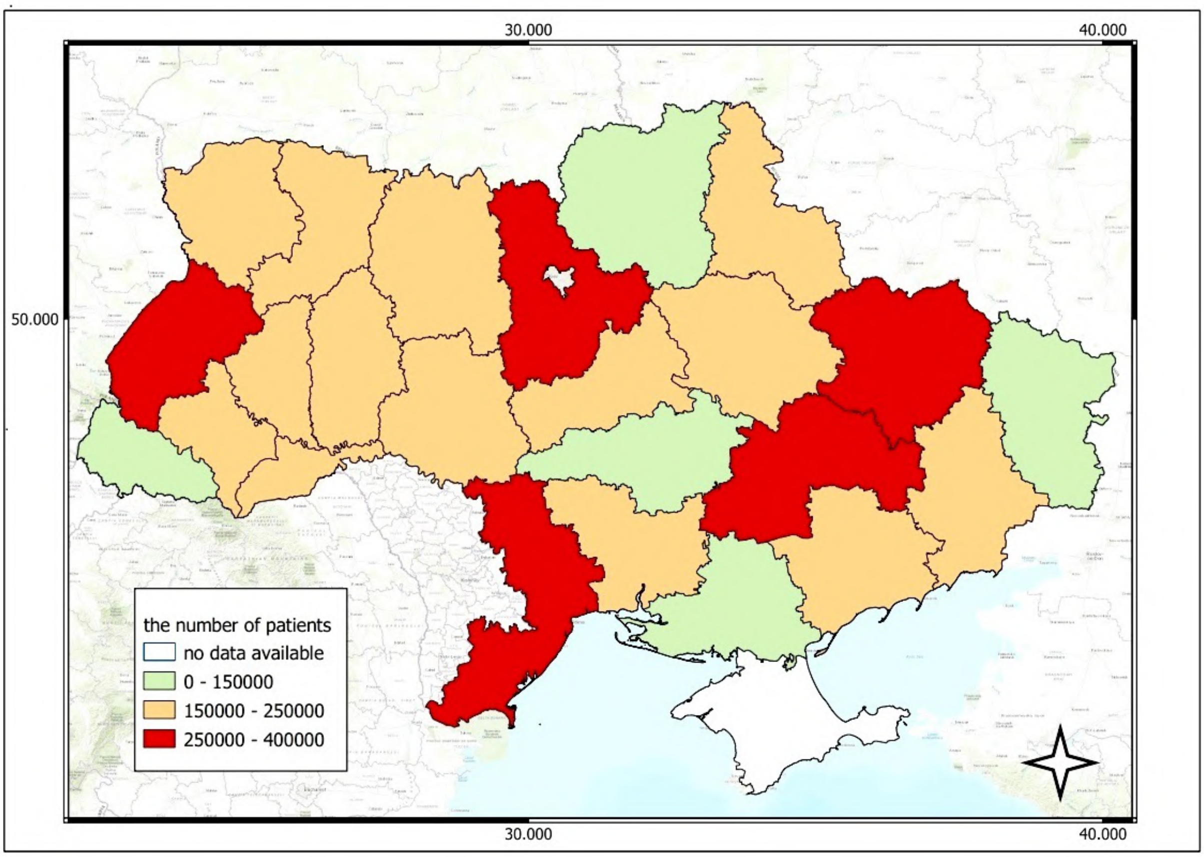

Figure 5. Horopleth map of the distribution of the number of detected cases of COVID-19 infection in the Ukraine at the end of the pandemic (data as of March 9, 2023).

According to the National Academy of Sciences of Ukraine, the Delta strain is 1.6 times more infectious and 2.26 times more likely to lead to hospitalization, but does not cause a significant increase in mortality. Over the course of several months, it gradually becomes dominant, displacing other coronavirus strains.

Mass vaccination against COVID-19 and restrictive measures in countries around the world served as deterrents to the significant spread of the virus, so the number of confirmed cases of infection during the third global wave was the lowest at 65 million. Global mortality rates were also the lowest, amounting to about one million deaths. Despite the fact that the spread of Delta began in India, it spread most widely in the United States, Brazil, European countries (UK, Portugal), and Russia. Therefore, the number of infected people at the peak of the wave (as of September 1, 23) increased in the United States to 40 million, Brazil to 21 million, the United Kingdom to 6.8 million, and so on.

The Delta strain entered Ukraine only at the end of June 2021, so the third wave began a month later than the global wave (beginning in August 2021, ending in December 2021), and the peak shifted by almost two months (late October – early December 2021).

The country's healthcare system could barely cope with the high epidemiological burden caused by the Delta strain. During the relatively short period of the third wave, 1.23 million people were infected in Ukraine, and almost 43,000 died.

The overall picture of the virus spread at this stage is broadly similar to the previous period. The most populated regions are leading in terms of infection rate (as of December 1, 21): Kharkiv (235914), Odesa (228750), Lviv (210153), Dnipro (233290) and Kyiv (147887) regions. Zaporizhia (172575) and Donetsk (155732) regions are close to them. The lowest figures were recorded in Kirovograd region (29854).

In general, a characteristic feature of this wave is the spread of the disease from the center to the periphery, not only across the country as a whole, but also within regions. Thus, at this stage, the number of patients in rural areas of Ukraine has increased significantly. The fourth global wave of morbidity lasted from the beginning of November 2021 and ended in April 2022 (peak in January 2022). It is associated with a new dominant strain, Omicron. This strain is highly contagious compared to previous coronavirus mutations, but the course of the disease after infection is mild. As a result, the number of confirmed cases during the fourth wave was the highest at more than 240 million, but the mortality rate was one of the lowest (1.13 million).

Similar trends have been established for the incidence rates of the fourth wave of the pandemic in Ukraine. It took place a month later compared to the global wave (beginning in December 2021, decline in April 2022, peak in February 2022). More than 1.38 million people were infected, with 12.5 thousand deaths.

The geographical distribution of confirmed cases and deaths has hardly changed. At the end of the pandemic, according to WHO, the five countries most affected by coronavirus infection were: The United States (109 million cases), India (45 million), France (40 million), Germany (38 million), and Brazil (38 million). If we analyze the quantitative composition of the thirty countries with the highest incidence rates, most of them are from Europe (12) and Asia (10). In terms of the absolute number of cases, the countries with the largest populations are leading the way. Only African countries are absent from this ranking. It is worth noting that, for the most part, regional patterns of the pandemic, both at the country level and at a larger scale, are almost identical. In general, they correspond to pandemic waves and differ only in the intensity of the pandemic indicators, and may also shift in time depending on the region's exposure to the pandemic wave.

The development of the pandemic in Ukraine is an example of this. Thus, the spatial differentiation of the number of detected cases of COVID-19 infection in Ukraine at the end of the pandemic (figure 6) generally corresponds to the distribution of the population by regions of the country in the pre-war period: the regions with the largest population have the highest number of cases (Dnipropetrovsk region – 372339 infected; Odesa – 356835; Kharkiv – 322502, etc.) and, accordingly, the regions with the smallest population have the fewest cases (Kirovohrad region – 59243 infected; Kherson region – 110926; Zakarpattia region – 130309, etc.) At the same time, the nature of the histograms showing the temporal change in the number of confirmed cases of infection is almost identical for all regions of Ukraine and differs only in absolute terms of the pandemic.

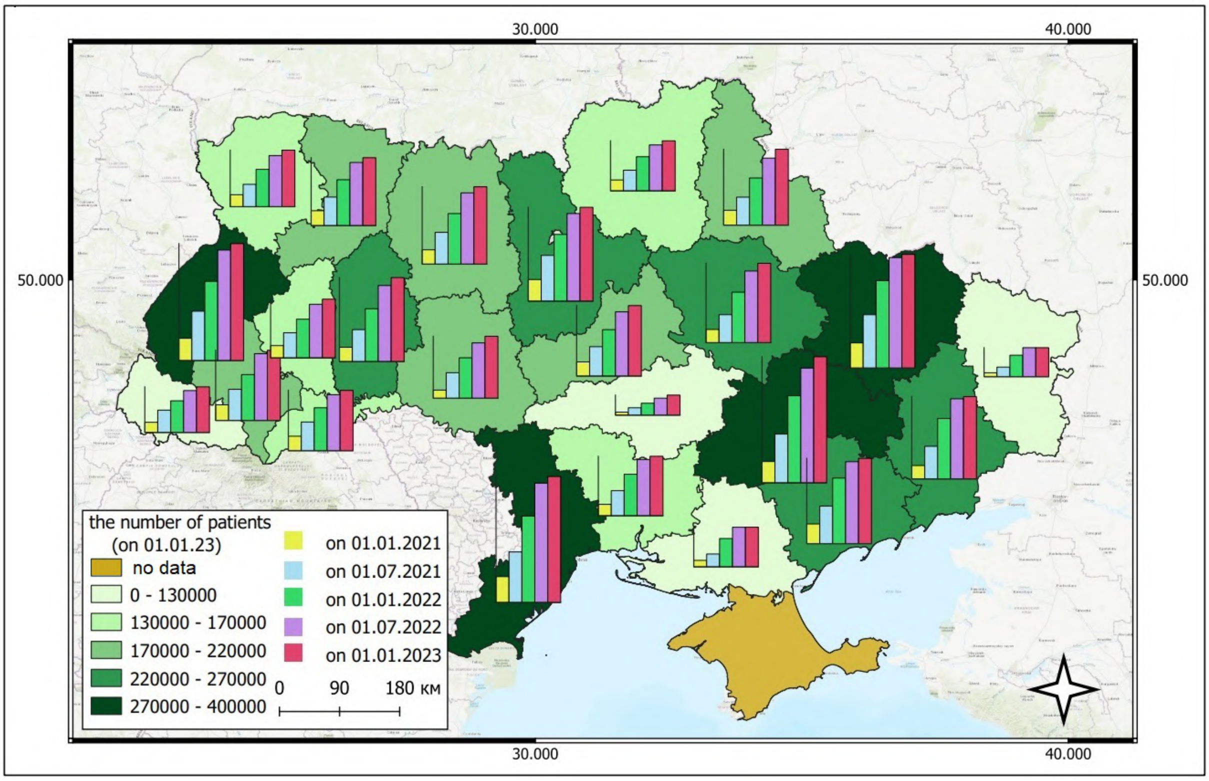

Figure 6. Spatial and temporal change in the number of confirmed cases of infection with COVID-19 in Ukraine.

However, it should be noted that since February 24, 2022, Ukraine has experienced very active processes of migration from the war zones due to Russia's military aggression. Also, part of the country's territory was and is under occupation. Therefore, if we analyze the map of the distribution of the number of detected cases of COVID-19 infection to the number of people (according to the data as of February 24, 22) in the regions of Ukraine (figure 7), we can clearly see the zonal distribution of this indicator: its value increases in the directions of south → north and east → west. This spatial differentiation is explained by migration processes. The number of people and, accordingly, the number of COVID-19 cases in the northern and western regions has increased significantly due to migration from the frontline areas in the south and east of Ukraine.

The main consequence of the coronavirus is a sharp increase in global mortality. According to the WHO, at least 7 million people have died during the coronavirus pandemic. However, as most pandemic researchers suggest, the real number of deaths could be three times higher than the official estimates, amounting to about 20 million people.

The choropleth map of coronavirus deaths actually duplicates the map of the spread of the infection in the world (figure 4). The main reason for this is the close correlation between the total number of infected and deaths. The correlation coefficient is +0.88, but there are exceptions. For example, in France and Germany, the number of deaths is lower than the average model indicators by less than 200 thousand people, and in North Korea and Japan by almost 300 thousand people. At the same time, in Russia, these figures are 100 thousand deaths

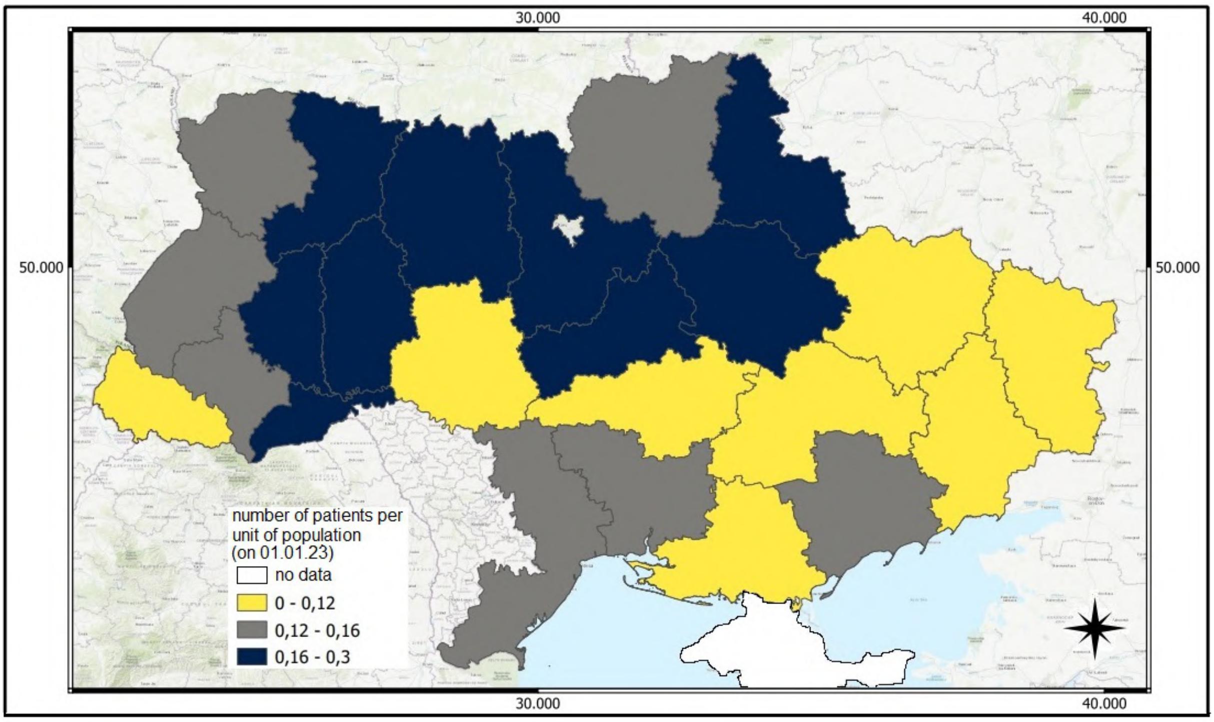

Figure 7. Horopleth map of the distribution of the number of detected cases of infection with COVID-19 by the number of the population in Ukraine at the end of the pandemic (data as of March 9, 2023).

higher than the average, and in Mexico and Peru, they are almost 200 thousand deaths higher. This demonstrates the different levels of healthcare systems in these countries.

The map showing the spatial differentiation of mortality from COVID-19 looks radically different (figure 8). This indicator shows the number of deaths from the coronavirus relative to the total number of patients from the pandemic for each country. In fact, this indicator demonstrates the effectiveness and accessibility of the social security and health care system in countries around the world.

The average death rate from coronavirus in the world was 0.99%. Most countries in Africa and Latin America have the highest mortality rates. Anti-leaders: Peru – 4.92%, Mexico – 4.37%, Yemen – 18.07%, Sudan 7.89%, Egypt – 4.77%, Liberia – 3.65%, Ecuador – 3.37%, etc. With low and very low rates of total COVID-19 cases, almost one in twenty people who contracted the coronavirus died on average in these countries. This illustrates the inability of the healthcare system in these countries to cope with such an epidemiological burden.

For comparison, the mortality rate in South Korea is 0.1%, Qatar – 0.15%, Japan – 0.22%, Denmark – 0.28%, etc. These countries have developed social security and health care systems that have coped with the epidemic even during the peak stages of overload due to the pandemic.

In Ukraine, there is also a high correlation between the number of detected cases of COVID-19 infection (figure 5) and the number of deaths from the disease: the regions with the highest number of cases have the highest number of deaths. For example, out of the 112478 deaths from coronavirus in Ukraine as of 29.06.23, 9.1% (10187 deaths) were recorded in Dnipropetrovsk region, 6.6% (7404 deaths) in Kharkiv region, 6.2% (6931 deaths) in Lviv region, and 5.5% (6206 deaths) in Odesa region. Accordingly, the lowest rates were recorded in Kirovohrad (1936 deaths, 1.7%) and Ternopil (2482 deaths, 2.2%) regions.

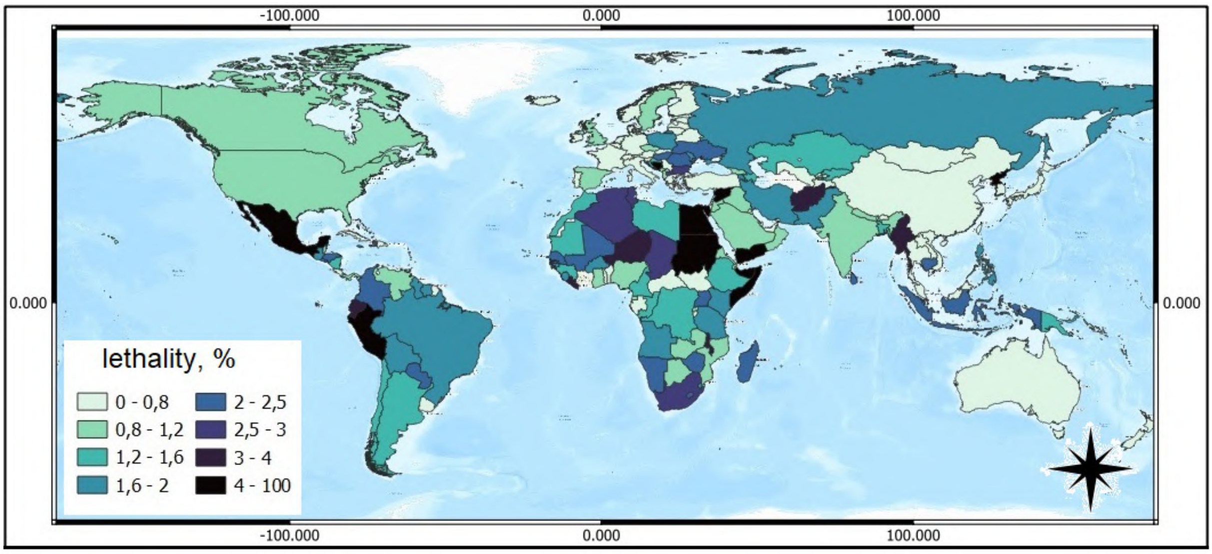

Figure 8. Horopleth map of the distribution of the lethality rate from COVID-19 in the world at the end of the pandemic (data as of March 9, 2023).

As of 29.06.2023, the coronavirus mortality rate in Ukraine averaged 2.02%, which is more than twice the global rate (0.99%). The highest mortality rate from coronavirus was recorded in Kirovohrad (3.27%), Luhansk (2.98%), Dnipro (2.74%), and Kherson (2.65%) regions. The lowest rates were recorded in Rivne (1.37%), Ternopil (1.47%), and Volyn (1.57%) regions. As a result, there is a pronounced spatial differentiation of COVID-19 mortality rates on the map of Ukraine (figure 9): the southeastern and eastern parts of the country have the highest mortality rates (over 2.3%), and the northern and northwestern parts have the lowest (less than 1.7%). The rest of Ukraine has average rates.

Ukraine is characterized by a correlation between the number of infected people and COVID-19 deaths by region (correlation coefficient +0.85): mortality in the regions increases in direct proportion to the number of infected people. However, there are regions where this relationship is significantly disrupted. For example, mortality in Zaporizhia region is almost 2000 people higher than the average correlation, in Donetsk region – 1800 people, in Dnipropetrovsk and Kirovohrad regions – 1000 people, etc. At the same time, in Odesa region, the mortality rate is more than 2000 people lower than the calculated one. This demonstrates the different capacity of the health care system in the country's regions.

According to the quantitative characteristics of the two main indicators of the epidemiological course of the COVID-19 pandemic (the number of detected cases and mortality), all regions of Ukraine (except for the temporarily occupied territory of the Autonomous Republic of Crimea) can be divided into four groups (figure 10):

Group I (Zakarpattia, Chernihiv, Kirovohrad, Kherson, and Luhansk region) – regions with the lowest number of patients with coronavirus infection (less than 150000 people) but with an above-average mortality rate (< 2%). With their low population density, these regions have demonstrated difficulties in the healthcare system's ability to withstand such an epidemiological burden.

Group II (Sumy and Cherkasy region and most regions in the western part of Ukraine: Volyn, Rivne, Zhytomyr, Ivano-Frankivsk, etc.) – have the lowest mortality rate (> 2%) with average numbers of detected cases (< 150000; > 250000). These are the regions with the best epidemiological situation of the pandemic.

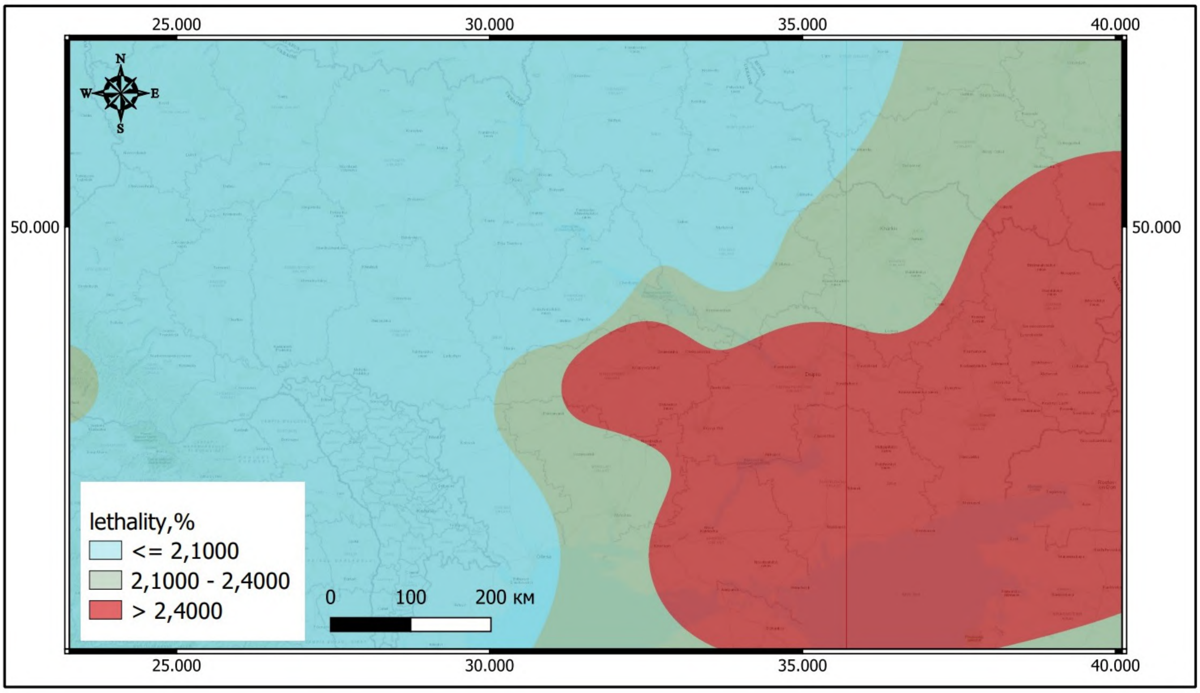

Figure 9. Map of spatial analysis of changes in the indicator of lethality to COVID-19 in Ukraine, based on the use of the incremental method (IDM).

Group III (Chernivtsi, Vinnytsia, Mykolaiv, Poltava, Zaporizhia and Donetsk regions) – characterized by mortality rates above 2%, with an average number of detected cases (< 150000; > 250000).

Group IV (Kharkiv, Dnipro, Kyiv, and Lviv regions) – regions with the highest mortality (< 2%) and morbidity (< 250000) in Ukraine. These are the regions with the highest population density and, accordingly, the most difficult epidemiological situation.

The course of the pandemic in Odesa region should be noted separately. With the largest number of detected cases (almost 360000), the mortality rate in the region was recorded at 1.74%. This can be explained by the most favorable climatic and environmental conditions in the region.

Based on the results of the geospatial analysis, a zoogeographical map of Ukraine's zoning according to the epidemiological course of the COVID-19 pandemic was constructed (figure 11), which reflects the spatial differentiation of the pandemic parameters, which is associated with various and multidirectional factors that determine the course of the epidemic, the main ones being:

A. *Population density.* Regions with the highest population have the highest morbidity and mortality rates.

B. *Spatial mobility of the population.* External and internal migration of the population has had a significant impact on the spread of the disease.

C. *Peculiarities of regional management.* The development of the epidemiological situation was largely determined by the quality of management decisions made by regional and city authorities (the state of the health care system, the behavior of the population during the lockdown, holding mass events, etc.)

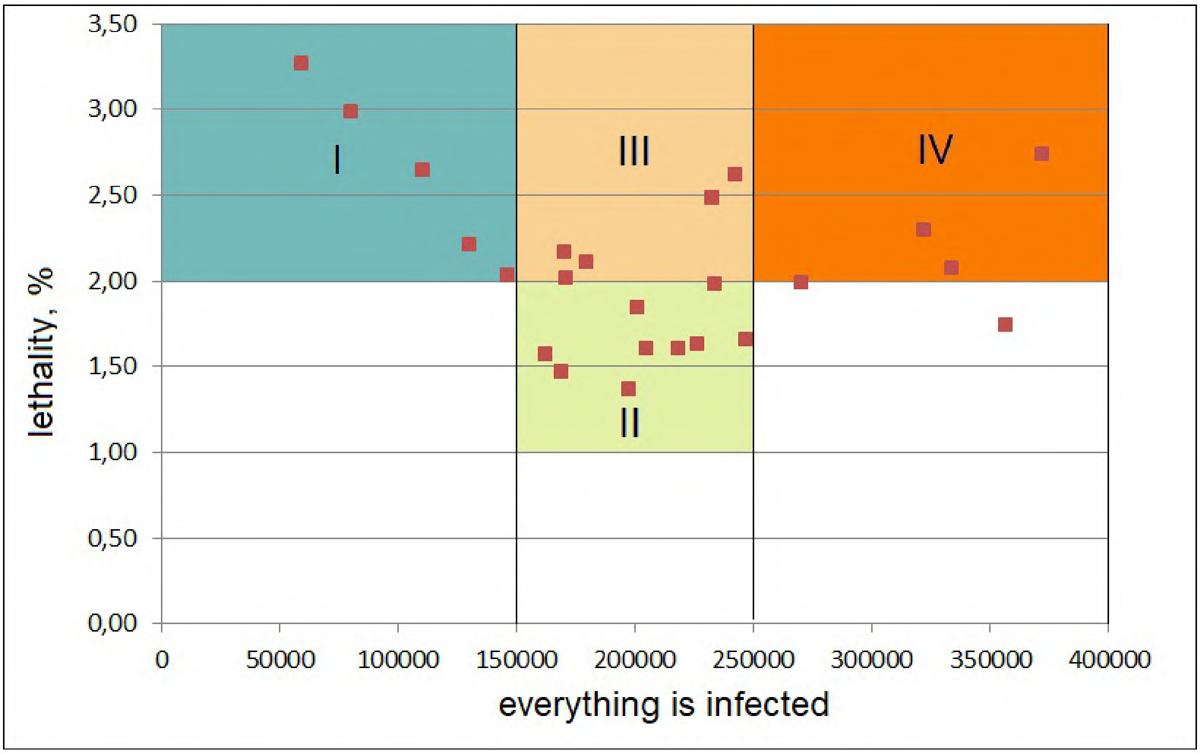

Figure 10. Classification of regions of Ukraine based on indicators of epidemiological transition of the COVID-19 pandemic.

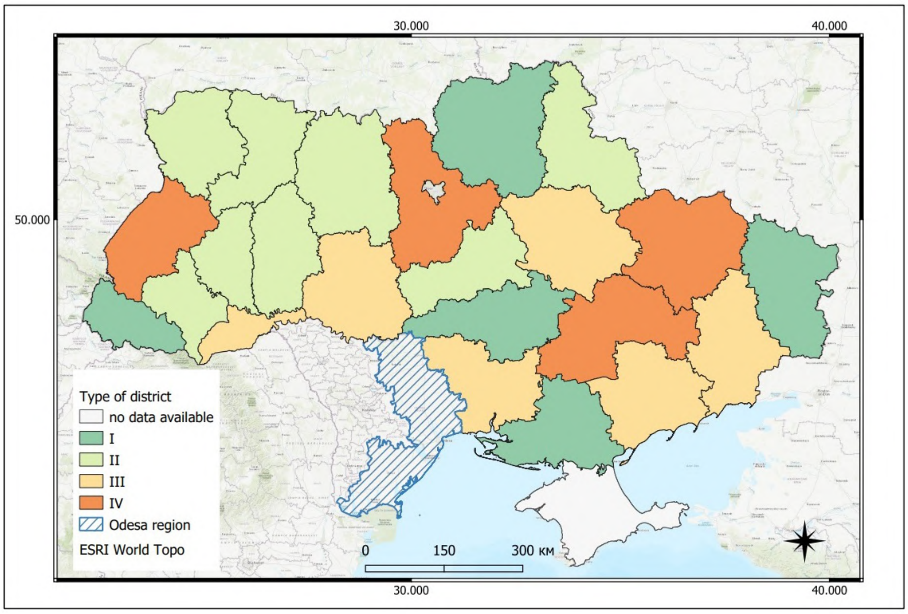

Figure 11. Map of the zoning of Ukraine according to the epidemiological course of the COVID-19 pandemic (classification indicators for each group are shown in figure 10).

4. Conclusions

The study of the geography of the COVID 19 pandemic in Ukraine and the world has led to the following conclusions:

1. The COVID-19 pandemic has its own geography, which is manifested in the spatial and temporal model of regional development.
2. The global nature of the coronavirus pandemic makes it impossible to study its development in a single country in isolation from global realities. Comparison of the dynamics of growth in the number of detected cases of coronavirus infection in the world and Ukraine shows that the pandemic is wave-like, but the amplitude, period, and length do not coincide in most cases. However, the genesis of these waves is the same.
3. Each of the waves of the pandemic in Ukraine had its own characteristics:
   - during the first wave, carriers of the coronavirus – Ukrainian workers from European countries – played a major role in the spread of the disease, who began arriving in big amountsin the western regions of the country after the announcement of lockdowns in Europe;
   - high population density in a number of regions, as an indirect indicator of social contacts, was the main factor in the spatial differentiation of pandemic indicators during the second wave;
   - a characteristic feature of the third wave is the spread of the disease from the center to the periphery, not only across the country as a whole, but also within regions; it is associated with the spread of the Delta strain and is characterized by high rates of disease, without a significant increase in mortality;
   - the fourth wave was distinguished from the previous ones by a very rapid rise and rapid decline, it is associated with the Omicron strain; its peculiarity is the highest incidence rate with the lowest mortality rate.
4. Significant spatial and temporal differentiation of the pandemic parameters is associated with diverse and multidirectional factors that determine the course of the epidemic and the spatial differentiation of its indicators.

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Features of the functional zoning of esports arenas taking into account the concepts of sustainable development of territories

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Abstract. The development and digitalisation of modern society have created the necessary preconditions for the emergence of new hobbies and sports. Esports has become an integral part of society and is officially recognised at the state level in several countries, including Ukraine. That is why the question arises of the emergence of esports arenas as a new type of architectural typology of public buildings and structures. This publication is devoted to studying the peculiarities of functional zoning of esports arenas, considering the concept of sustainable development of the territory. The article analyses existing esports arenas, computer clubs in the world and Ukraine, and approaches to the organisation and functioning of esports championships. The needs of players and spectators for creating a comfortable space and convenient functional planning of esports arenas are investigated, considering the concept of sustainable development of territories. The proposed solutions are analytical and conceptual, requiring a detailed development of constructive, architectural and design solutions, considering the current standards for public buildings and structures.

1. Introduction

Rapidly developing modern technologies provide unlimited opportunities for finding new solutions and innovations in developing Ukrainian architecture. Recently, eSports, which improves and trains mental and physical skills, has gained momentum, being a mass spectacle with innovative technical aspects and information technologies. The digitalisation of society and the development of information technology have led to the need for entirely new facilities, such as an esports arena. When designing and building such facilities, it is necessary to use the main provisions of sustainable development of territories based on the unity of economic, social and environmental components of the concept to meet the modern needs of humanity and protect the interests of future generations.

An analysis of the competition procedure, requirements for technical equipment and facilities, the current state of buildings and facilities used for esports championships, and the constant growth in demand and the number of teams revealed the inadequacy of existing facilities, such as concert halls and sports stadiums, and created the prerequisites for a functional zoning study for the design and construction of an esports arena that would meet the modern needs of society, taking into account the requirements of sustainable development of territories.

There are few newly created and operating esports facilities in the world. At the same time, a significant number of facilities are currently in the process of planning, modernisation, development and implementation. The volumetric and spatial structure and functional zoning solutions for existing and future esports facilities are insufficient in Ukraine and, therefore, require careful analysis and research as a new type of public facility.

Esports facilities are an innovation in architecture. Until recently, architectural objects such as an esports arena (cyber arena) did not exist but were implemented as an option for expanding and modernising such facilities as computer clubs. However, more is needed for modern technologies and championships. Publications and research on zoning cyber arenas exist in related fields, including information technology, computer networks, cybersecurity, and sports. Therefore, it is relevant to find new scientific solutions and construction and architecture technologies for implementing such technologically innovative structures, considering the concept of sustainable development of territories.

Therefore, the purpose of this publication is to study the peculiarities of functional zoning of esports arenas by analysing existing esports arenas, computer clubs in the world and Ukraine, approaches to the holding and functioning of esports championships, and the needs of players and spectators to create a comfortable space and convenient functional planning, taking into account the concept of sustainable development of territories.

2. Theoretical background

Today, esports is developing rapidly, requiring new training and competition areas. Many countries worldwide pay attention to esports and create cyber arenas for training and competitions [1–4]. In Ukraine, many computer clubs and cyber arenas, including international ones, serve as training grounds and venues for competitions.

An esports arena is a multifunctional building with special requirements for functional planning. The physical dimensions of such a facility and functional zoning are determined based on the location and are related to the requirements of the concept of sustainable development of territories.

Given the rapid development of the digitalisation of society and the development of information technology, it can be stated that modern architecture is characterised by a continuous process of creating new types of architectural objects, the vast majority of which have a short life cycle [5]. Buravchenko and Barmashina [5] presented a new paradigm of architectural topology, the essence of which is the use of three "alternative to traditional typologies of the latest directions of the methodology of forming architectural objects" [5], namely the use of the parametric (scenario) method, the methodology of analysing types of architectural environment and typological differentiation. When designing this kind of building, it is necessary to explore the possibilities of its multifunctional purpose (formation of a multivalent space).

Creating a multivalent public space surrounded by mono-functional enterprises integrated with an esports arena, taking into account the concept of sustainable development, is significant scientific research in the field of the architectural environment [6–9]. Buravchenko [6] presents approaches to creating a universal methodology for designing multivalent public spaces with cyclical function changes. The author conducts a study of urban space optimisation with the aim of optimising and functional zoning for each specific period of the year and predicting its use for the interests of different communities.

Considering the conceptual provisions of Ukraine's Sustainable Development Goals [7] implies compliance with specific requirements for developing new territories. Among them are the preservation of the environment and natural resources and the creation of social benefits. When developing design solutions, it is necessary to consider the achievements of modern science and technology, information technology, the level of informatisation of society, and the architectural environment [8, 9].

Architectural solutions for the design of esports arenas are developing quite rapidly, particularly in Asia, the USA, and Europe. Dorosheno and Titova [10] presents a study on identifying an esports arena's architectural components and briefly describes architectural planning.

3. Results

Computer technology has reached a new level in technical fields and the gaming industry. As computer games became more accessible, Internet clubs emerged, allowing several gamers to play simultaneously online. These clubs also began hosting gaming competitions, bringing spectators and participants together. As the alternative universe gained more and more popularity among young people, gamers began to find venues for tournaments, as there was not enough space in online clubs.

The events currently taking place in Ukraine hurt the architecture of cities and villages. The destruction of buildings, architectural monuments, and other structures negatively impacts the architectural environment and requires the development of restoration, reconstruction, and development projects. Ukraine currently needs many vital resources but will need even more after the war ends. Resources are needed to rebuild cities, infrastructure, and many other economically important factors.

A multifunctional complex combines the necessary buildings and structures into one whole, minimising the time spent moving from one place to another. This is especially important in a large city, creating a single cultural, sports, and recreational centre for the community.

Esports facilities are an innovation in architecture. Until recently, architectural objects such as esports (cyber arena) did not exist, but they were implemented to expand and modernise facilities such as computer clubs. However, more is needed for modern technologies and championships.

The following aspects should be taken into account when designing a multifunctional complex with a cyber arena:

- location: analyse where the complex will be located;
- functional content: analyse the needs of the city's population;
- planning: to create planning solutions based on the analysis of the needs of cyber competitors, spectators, and requirements for competitions and training;
- integration: to determine the type of facilities, their number and purpose, methods and technologies for combining several structures and buildings into a single complex;
- safety: to provide civilians with quickly accessible and comfortable shelters, as well as to make them accessible to people with limited mobility;
- sustainability requirements: to provide an environmentally friendly, comfortable to use and favourable for development and living environment with architectural and design solutions;
- environmental safety: selecting materials for construction, design, and finishing that are environmentally friendly, durable, and high-quality.

We will analyse foreign and domestic design experience to implement the design of a multifunctional complex with a cyber arena.

An essential aspect of the recovery is public facilities where people can develop, do their own business, work, and relax, which is considered a whole life. It is worth noting that many people who have been forced to leave the territory of Ukraine and live abroad should return to Ukraine. To do this, it is necessary to create comfortable living and development conditions, considering the modern needs of young people. An analysis of the latest youth trends and preferences shows the diversity of their interests, among which eSports occupies a special place. Therefore, building a modern multifunctional complex with a cyber arena is essential.

Let us analyse the experience designing and implementing esports facilities worldwide and in Ukraine. To begin with, let us look at Blizzard Arena Los Angeles (Burbank, California, USA), which was included in the ranking of the world's best cyber arenas, the interior of which is shown in figure 1. It was here that Overwatch League tournaments were held. The arena was quite famous, but at the same time, its main drawback was the small capacity of the spectators; only 450 people could attend the match, although thousands of online viewers gathered during the broadcast of the tournaments. The area of the arena is 6875 m^2, and the central stage area is 1000 m^2. In the centre of the stage, a 13,000-pixel wide LED screen was installed to show the game's events, with an LED halo above the stage showing the progress of the upload during each round of Overwatch. The audience's proximity to the centre stage and a vast skybox was a unique feature. Given the specifics of holding esports games, matches and tournaments and the need to broadcast them, an essential aspect of the design is the support area (control rooms, sound rooms, communication rooms, server rooms, and observation rooms).

Figure 1. Interior of Blizzard Arena Los Angeles [4].

In 2010, one of the first esports arenas in the world was opened in Ukraine, which became the impetus for the massive construction of similar arenas around the planet, the interior of which

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is shown in figure 2. This arena can accommodate about 3000 spectators, which generally meets the needs of the audience. The building of the Kyivsport Arena consists of:

- entrance area;
- a corridor leading to the main hall;
- main hall with an area of 1500 m^2;
- gambling shops;
- A commentary booth is located in the hall.

This arena had a dual purpose: it was used as a computer club and a venue for gaming championships. The main hall was mainly equipped as a gaming club, based on individual computer seats, and there was also a screen for broadcasts with a small number of seats for spectators. For large-scale championships, the main hall was arranged in such a way as to create the most comfortable conditions for participants and spectators, reducing the number of computer seats. A significant drawback of this arrangement is the players' need for more sound insulation. One solution to this problem was using sound-absorbing headphones, which only partially satisfied the teams.

Figure 2. Interior of the Kyiv Esports Arena [4].

Arlington Esports Stadium (figure 3) is the first full-fledged esports arena that meets all the needs of both gamers and spectators. It was opened in 2018 in the state of Texas.

It is divided into functional areas according to their purpose and includes

- team area
- lounge area for teams
- training rooms
- media zone
- area for communication with fans

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Figure 3. Interior of the Arlington Esports Stadium [4].

- shop area
- gamer gallery
- auditorium
- production area
- VIP area
- zone for content creation
- technical zone

An essential factor of the competition is the availability of an individual recreation area for participants and guests. That is why the advantage of Arlington Esports Stadium is its location next to the sports complex and hotel.

Spodek Arena is an arena that serves as a hockey stadium and is currently used for esports tournaments in Katowice. It has a capacity of 11-12 thousand spectators, but 2017 at the Intel Extreme Masters Grand Final, it accommodated about 170 thousand spectators. The interior of the arena is shown in figure 4.

One of the most widespread cyber arenas located in Las Vegas is Esports Arena Las Vegas (figure 5). Its area is more than 9000 m^2, and the interior is shown in figure 5 and figure 6. This multi-level arena has a competition area, a zone for daily tournaments, modern broadcast and production studios, VIP rooms and telescopic seats. The arena also features the interactive zone “History of Gaming Dome”. It includes retro games and a gaming platform.

With the opening of Esports Arena Las Vegas, a new standard of professional sound in the gaming industry has been set, which delights gamers and their fans. Shops are located on the territory.

Gaming seats, broadcast stands, and retail outlets are located in the central hall of this area.

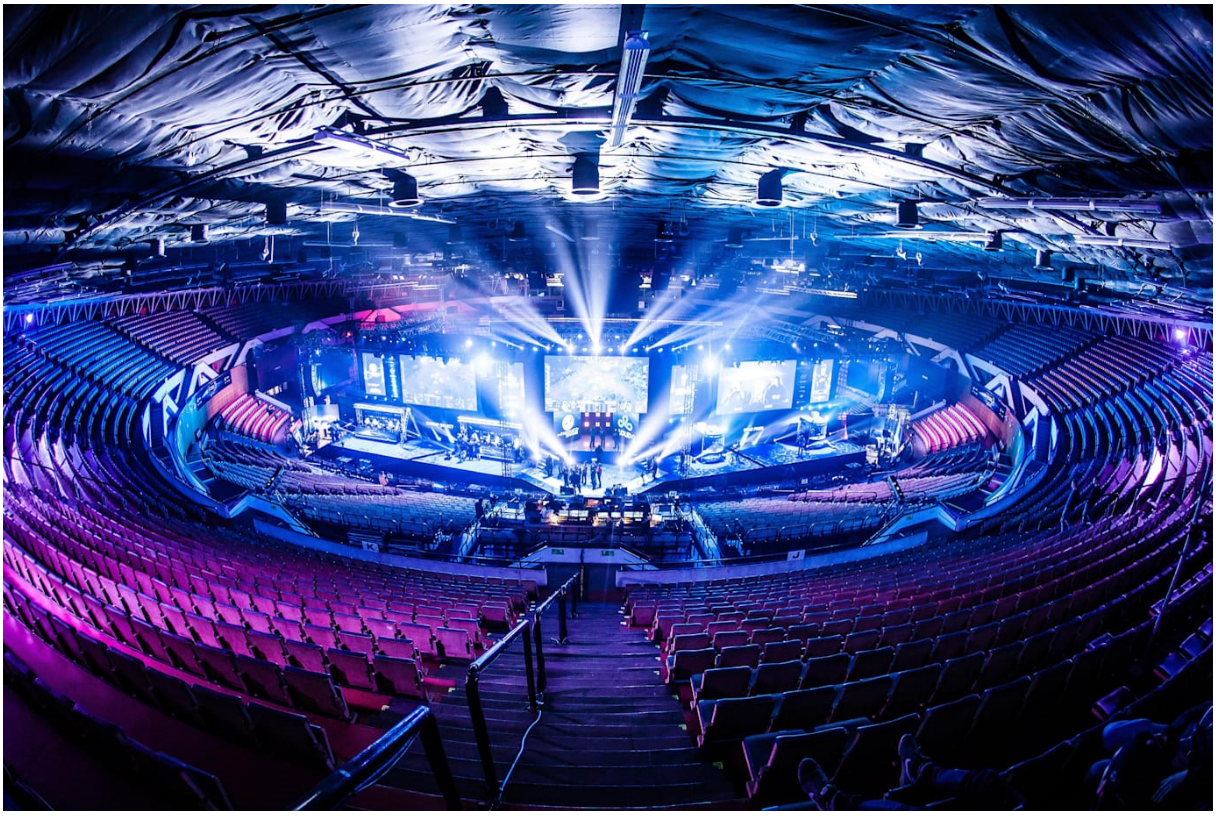

Figure 4. Spodek Arena interior [4].

Such a high demand in this area demonstrates the relevance of this problem and the prospects for developing esports as an independent area of architecture and design, which requires streamlining regulations and standards for the design and construction of facilities in this area.

Visitors to esports arenas are divided into the following groups: regular, unique visitors, and athletes. The regular attendance group includes employees of the complex and visitors who come regularly, regardless of the championships. Unique visitors are those who come to the championships and festivals. Esportsmen can come to championships and festivals or stay and train seasonally.

As a result of the study, we identify the main functional areas for a cyber arena, namely:

- The main arena, including the stands, stage, and commentary room. The tribune should be divided into two parts. Each team consists of 5 people: one coach and one technical support. The team should sit facing the audience.
- Training centre (often used for qualifying tournaments).
- Rooms for players (boot camps) must be soundproofed and equipped with climate control, but it is not mandatory to have window structures. Since a boot camp is designed for one team (7-8 people), an esports complex needs two.
- The lounge area is a recreation area that should be located near the players' room and can sometimes be included in the boot camp.
- Common areas.

Common areas include:

- Shops.

Figure 5. Esports Arena Las Vegas [11].

- A place for photo shoots.
- Dining room.
- Marketing area.
- Technical rooms: central server room; room of system administrators, engineers and programmers who serve them; media centre (video broadcasts); server room with special equipment; sound and light department.
- Lobby.
- Wardrobe.
- Storage rooms.
- Administrative premises.
- Bathroom for visitors.
- Bathroom for players.
- Changing rooms for teams.
- Medical rooms.
- Cafe area.
- Halls for special physical training.

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Figure 6. Esports Arena Las Vegas [11].

Given the need for a constant power supply, it is essential to consider alternative ways of connecting to the electricity supply. As a rule, teams rent separate apartments or hotels for accommodation, install computers, and connect high-speed Internet. When designing an esports complex, it is worth considering a hotel as a complex component. It is also mandatory to have a psychologist's office. An analysis of the approaches to constructing the world's famous cyber arenas has identified several functional features of buildings and structures and the need to consider Ukraine's Sustainable Development Goals when designing them. This study will serve as a basis for further design of esports arenas.

The main goals in designing cyberspace are:

1. To create a comfortable environment, taking into account the needs of athletes, athletes, spectators, visitors, and staff, paying attention to internal and external features, as well as design elements of the architectural environment.
2. The design of this building should be open and bright, and adaptable to changes in the

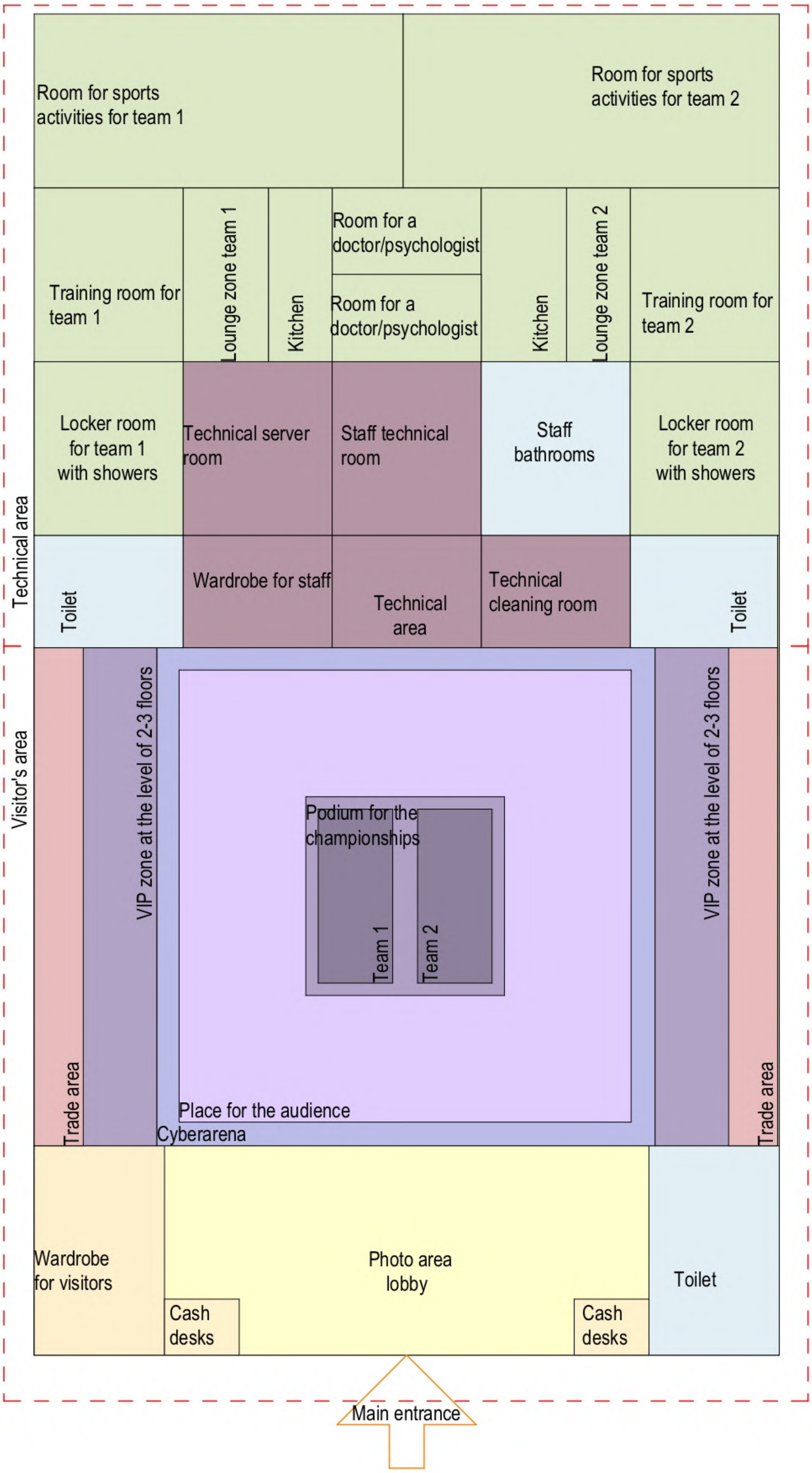

Figure 7. Scheme of functional zoning of the cyber arena (option 1).

functional purpose of the building.

3. Provide a vast visual space for a large number of people to stay together, as well as separate rooms for VIP areas.
4. It is also necessary to provide a zone of greenery in order to provide a comfortable environment for visitors and reduce the emotional stress of players.
5. The arena, training rooms and the room for teams to participate in the tournament should be soundproofed to ensure fair play.
6. It is necessary to think about a certain tendency to change the configuration of the arena for premises for various purposes.
7. It is necessary to provide a full-fledged place of residence for participants of championships

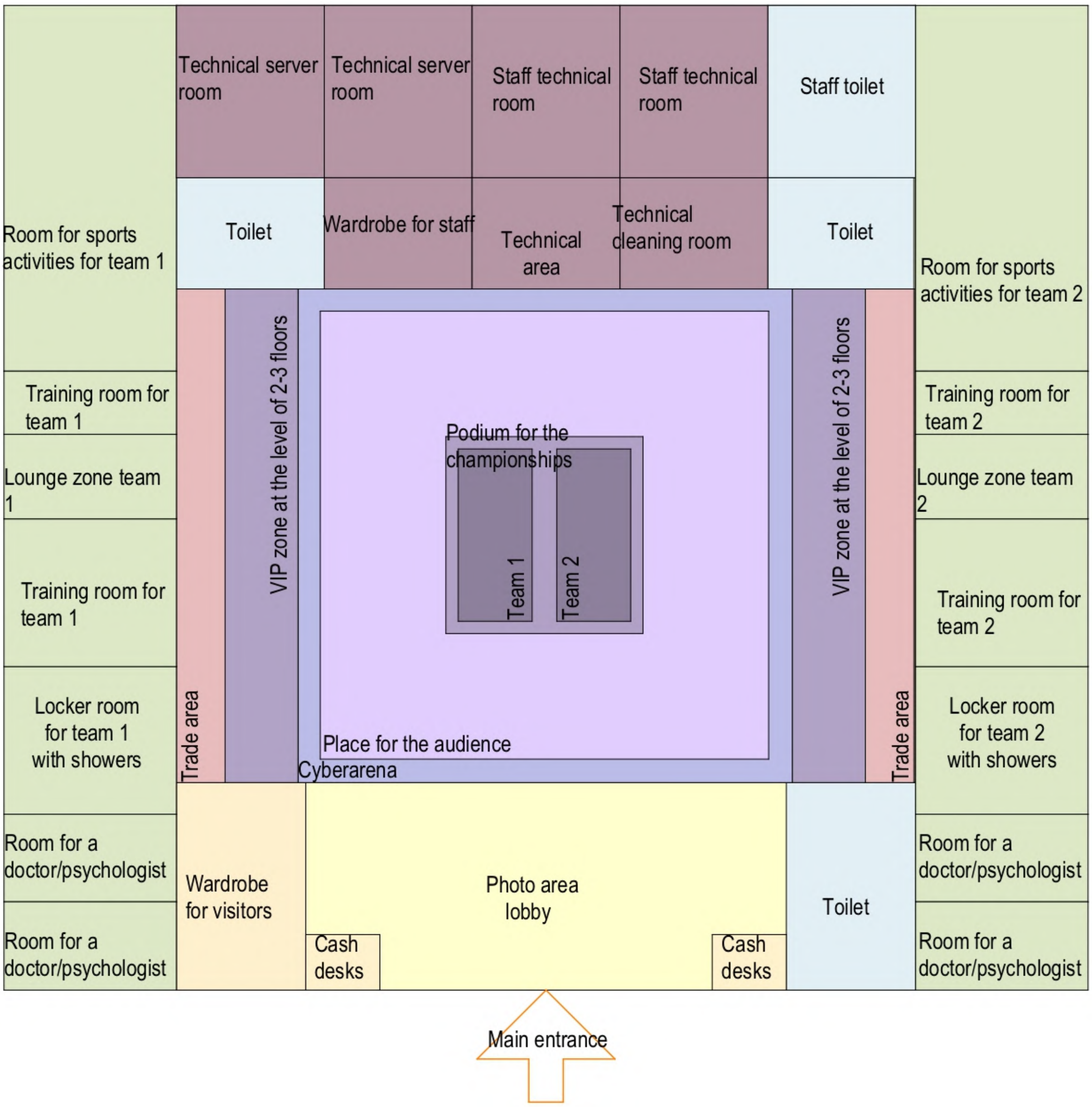

Figure 8. Scheme of functional zoning of the cyber arena (option 2).

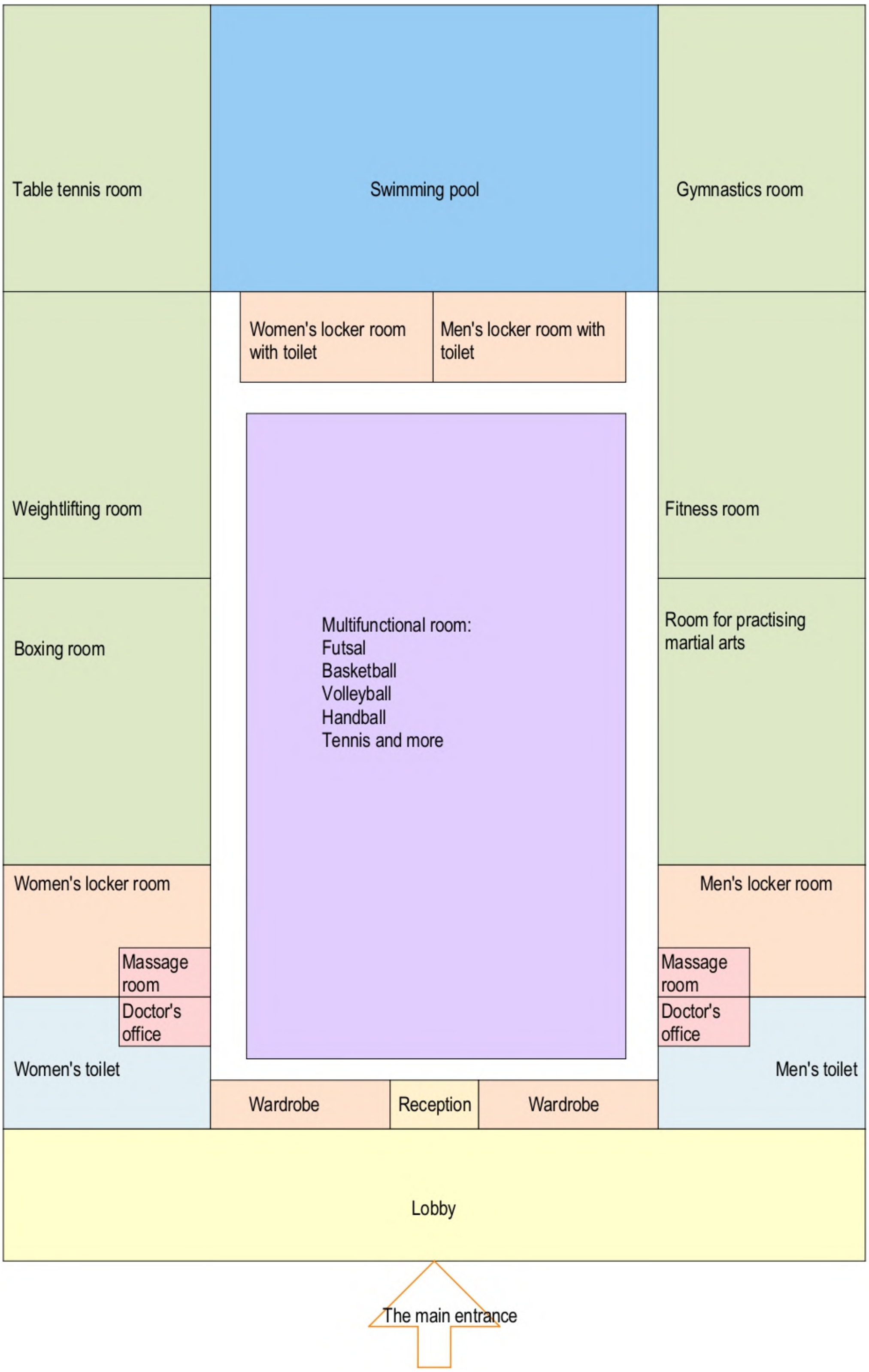

Figure 9. Functional zoning scheme of a sports complex with a multifunctional hall.

of various profiles, including esports.

8. Develop the necessary number of technical premises to ensure the functioning of the arena.
9. It is necessary to provide for the broadcast of events at the arena in the premises located inside and outside the arena and in the complex's parking area.

Taking into account the results of the analysis, current requirements, and identified features, three variants of the functional zoning scheme of the cyber arena were developed (figure 7, figure 8).

In the future, these schemes will be used as conceptual ones. We are developing a functional zoning scheme for a sports complex with a multifunctional hall for further research to find the optimal design solution, figure 9.

4. Discussions

The proposed solutions are analytical and conceptual, requiring more detail. In particular, the following issues require attention:

- researching approaches to the functional zoning of the interior and exterior of the esports arena;
- development of structural and electrical solutions taking into account the current level of science and technology;
- research of methods, algorithms, information and telecommunication technologies in order to create modern technical equipment for esports arenas for improvement;
- ensuring the protection of information for the proper functioning of such facilities;
- research of the processes of developing a master plan;
- development of a heating and ventilation scheme with the use of modern materials, approaches, and energy-efficient energy sources;
- conducting a feasibility study to optimise capital and operating costs.

5. Conclusions

Esports has become an integral part of our lives, directly influencing the development of other industries, especially architecture. The esports complex project's main objective is to meet society's needs and provide the most comfortable conditions for competitions and leisure. These are all prerequisites for the emergence of a new division in architecture in the field of esports.

Having analysed the specifics of esports competitions, we can identify the following functional features: the presence of a screen, which is the basis of any cyber arena and should be located without blind spots. Given the duration of the championship, there is a need for recreational areas for both visitors and players. Special attention should also be paid to the player's mental and physical health (one game lasts up to 12 hours). At professional competitions, players are isolated from spectators, so there is a need for additional rooms or acoustic booths.

To ensure the technical side of the esports complex, it is necessary to equip the building with server rooms, high-speed Internet and alternative power supply. It is also necessary to consider electrical outlets and a WIFI network for visitors.

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Resource-saving method of extracting cucumber and melon seeds

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Abstract. The production of vegetable and melon crops is one of the most labour-intensive branches of agricultural production. Production volumes depend not only on growing conditions, but also on the quality of seed material. A resource-saving method of extracting cucumber and melon seeds and a separator that allows its implementation are presented. The design feature of the separator is a combination of vibration and inertial modes. The use of a separator, which has a combination of the mentioned modes in the technological process, allows to significantly improve the quality of separation of seeds from the peel and pulp. Thus, at the next stage, when washing the seeds, it is possible to reduce the amount of water, using the technology of a complete closed cycle of cleaning for reuse. The scheme of the technological process of cucumber and melon seed separation, which is used to implement a resource-saving method, is presented. The main factors and optimization criteria were determined, according to which the quality assessment of the technological process of cucumber and melon seeds separation was carried out using the proposed constructive solution. The ranges of the optimal combination of independent factors are determined. Using a resource-saving method of extracting cucumber and melon seeds allows to significantly reduce water consumption when washing seeds and achieve an improvement in the quality of the technological process.

1. Introduction

The production of seed material of melon and vegetable crops is one of the most important problems that have arisen in the field of processing agricultural products. In the southern part of Ukraine, there were specialized farms for the production of seeds of vegetable crops. The volume of this production of cucumber and melon seeds was significant and provided seed material to almost all farms of Ukraine. Thus, the development of seed production of vegetable and melon crops, such as cucumber and melon, will provide an opportunity to provide the economy of Ukraine with seed material. High-quality seed material is one of the conditions for increasing productivity and reducing the cost of cultivated products, and well-organized seed separation in farms increases the production crops by 20 ... 25%.

Enhancing the sustainability of the food system begins with boosting food production [1]. Moreover, it is crucial to offer the theoretical underpinnings of the corporate interaction management technique [2]. Practitioners interested in learning more about various water engineering models and approaches, as well as their real-world applications and case studies, can find valuable information in economy of water in technological processes [3]. There are presented and discussed is the evolution of the key accomplishments in water-saving engineering solutions, with a focus on the key technologies [4]. Ukraine is among the top producers and exporters of agricultural production in the world, and expanding production and the economy can both benefit from market integration between Ukraine and the EU [5–7]. For the environmentally friendly production of agricultural production, it is crucial to optimise the technological processes [8]. Farmers may decrease their carbon footprint, cut greenhouse gas emissions, and boost sustainable productivity through climate-smart agriculture [9]. Melon selection process, which prioritizes quality, plays an important role in obtaining a quality product. A technique that uses the relationship between parameters to provide descriptions and actions in determining melon quality is used to describe, extract, and share semantic information [10]. The possibility of short-wave near-infrared spectroscopy for fruit classification issues is examined in the research. When fruit categorization automation is needed, an LED-based device with 770 nm, 840 nm, 910 nm, and 960 nm range LEDs can be employed [11].

The production of seeds of vegetable and melon crops in Ukraine is carried out in the conditions of agricultural enterprises and farms. The obtained seeds of above mentioned crops today do not meet the needs of agriculture, and this leads to the need to purchase seed material. Separation of seeds is carried out mainly on separators of the mechanical type: inertial, rotary or roller. It has found limited use in the seed production of vegetable crops. Flotation separation is practically not used due to high water consumption and significant material capacity of technological equipment. Pneumoseparation is energy-intensive and time-consuming when converting separators from one culture to another. Inertial and rotary separators have approximately the same productivity and quality indicators of the technological process. The use of one or another type of rotary separators is related to the specifics of obtaining seeds of the crop, the volume of its production and the technical security of the farm.

Due to the lack of special equipment, machines not designed for this purpose are often used in labor-intensive seed production processes, which in turn leads to large product losses. The efficiency of production processes of seed separation and finishing is very low. The main reason for this situation is the lack of scientific research to substantiate the principle of action, structural parameters and kinematic modes of machines and their working bodies. Information is often contradictory. This state is largely due to the lack of generalizing theoretical and experimental studies of the processes of separation and finishing of seeds, which, accordingly, affected the development of machines and technological lines.

An analytical summary of all the components of the complete cycle of cultivation and processing was produced, ranging from a detailed investigation of the characteristics of melon cultivation to studies on enhancing technologies to produce high-quality seeds. Erniati et al. [12], for instance, investigated melanoculture and the ideal conditions for producing material of superior quality. The growing parameters received special attention in this study, which monitored plant age, leaf area, plant height, relative humidity, air temperature, and radiometric solar intensity to forecast these parameters for the next two days.

Research on growing melon and vegetable crops as well as useful methods for extracting seeds has received a lot of interest. To satisfy the demands of contemporary agriculture, high-quality vegetable and melon crop seeds are necessary to cut expenses and do away with the necessity to buy them from outside producers [13]. Wahyudi et al. [14] focused on yield estimation of novel hybrid watermelon cultivars. It has been demonstrated that producing melon seeds within an agricultural business can boost output and revenue for growers of the fruit. An essential part of a plant breeding programme is the examination and selection of seeds. Kale et al. [15] investigated the impact of the mechanical and technological characteristics of vegetable and melon seeds on the ensuing seed quality, whereas Fayzullaev et al. [16] showcased the creation of a machine for planting vegetable and melon crops. Tests have demonstrated that the created machine satisfies all performance requirements and carries out the designated technological procedure with reliability.

According to Tlevlessova et al. [17], the shift from large-scale farming to small-scale home

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growing has necessitated the introduction of cutting-edge scientific research and technology in order to produce high-quality seeds. The authors underlined that the shift in production from large agricultural operations to small private farms, which today account for over 90% of the total, is one of the major issues facing industrial melon seeds production. Simultaneously, small producers receive additional revenue from the transfer of output to the private sector, which could be their sole source of income. Private farms are more suited to the particulars of market interactions, as evidenced by the current state of affairs. A study was undertaken by Osuji et al. [18] to compare the processes of manual and mechanised seed separation for melon and vegetable crops. Using a press machine and a mechanical melon peeler, the seeds were peeled both manually and mechanically. It was determined how effective these devices were at extracting seeds. Out of all the automated procedures, the proposed design was the most productive. The cleaned seeds were assessed using technological and mechanical criteria. The results of the study demonstrated how important it is to select an appropriate variety, seed separator, and packing material in order to produce vegetable and melon seeds with optimal efficiency and quality. Kuchakorn et al.'s experiment from 2021 effectively separates ripe from unripe watermelons. The study focused on employing specialised equipment to determine fruit ripeness and if it was suitable for additional seed extraction [19]. The impact of native and germinated melon seeds on product quality is investigated in the paper [20].

Nascimento [21] pointed out that improving and preparing seeds can be a useful way to boost melon crops' survival rate. Particularly in cold climates, primed seeds perform better during germination. The author talks about a few factors of seed preparation and how they affect the germination and yield production of melon seeds [21]. Mazuela and Urrestarazu conducted experiments on improving the growing environment for vegetable crops in the context of studying the full cycle of vegetable and melon crops cultivation and seed production [22]. They noted that there is a need to increase the number of producers of vegetable and melon seeds. Getting hold of high-quality seeds contributes to higher yields, and grafting technology works wonders in lowering seed damage and yield losses. Lee et al. examined the topic of automating machines for cultivating vegetable crops [23]. The physical characteristics of vegetable crops have also been studied [24]. Thus, an essential component of the fields of food production and agricultural technology is the study of the physical characteristics of vegetable and melon crops and the methods used to measure them.

It is necessary to summarize the available experience in the development of machines for the complex mechanization of obtaining seeds of vegetable and melon crops, and on the basis of it to outline the main ways of developing and creating technological equipment. This will allow to increase the volume of production of seed material, will lead to a reduction of its losses in the process of production, storage and sale and ultimately will provide Ukraine with high-quality seeds. However, the creation of modern machines for the separation of seeds and technological lines that meet the requirements of modern production and belong to complex technical systems requires a deeper study of the interaction of working bodies with the processed product, the laws of the technological processes they perform, the dynamics and conditions of their operation. This task can be solved by conducting extensive theoretical and experimental studies of systematization and analysis of the achieved level of technical solutions. Thus, theoretical and experimental researches that allow to create modern, high-performance equipment for obtaining seeds of vegetable and melon crops are relevant and have an important national economic significance.

The aim of the article is to present the resource-saving method of extracting cucumber and melon seeds.

2. Methods

The methodology is based on the specific conditions for conducting experiments with the development and manufacture of the vegetable and melon seeds separator. To distinguish regular changes from random indicators, statistical methods of research and mathematical processing are applied [25]. For each experiment, 25..30 kg of crushed seed mass was selected, which was weighed, and the value of the selected weight was recorded in the log of laboratory and field observations. The main optimization criteria used to assess the quality of the technological process were: damaging of seeds (DS), purity of seeds (PS) and loss of seeds (LS). Their values must meet the following requirements:

- the amount of seed damaging should not exceed 5%;
- the value of seed purity should strive for the maximum level;
- losses should tend to the minimum value.

Before starting the experimental studies, the factors affecting the process were selected and the limits of their variation were indicated. In the initial stage of studying any object using the theory of experiment planning, it is necessary to conduct an a priory ranking of factors, which is performed by the method of expert evaluation (figure 1).

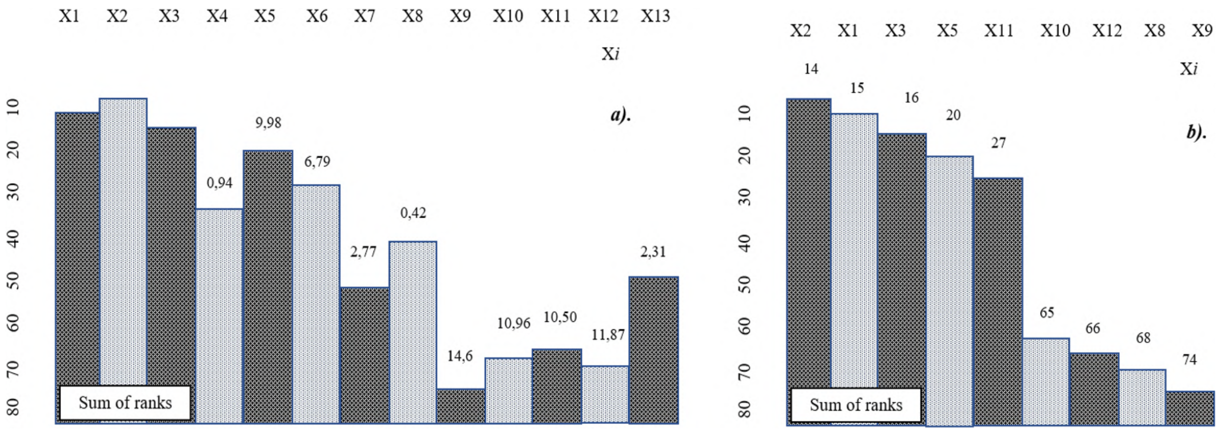

Figure 1. Ranking chart of factors affecting the quality of work A) to statistical assessment of the significance of factors; B) after ranking and determining insignificant factors.

There are the following factors:

X_1 – the angle of inclination of the sieve;
X_2 – frequency of sieve oscillations;
X_3 – amplitude of oscillations;
X_4 – level of mass supply for separation;
X_5 – the angle of application of driving force;
X_6 – the length of the sieve;
X_7 – sieve material;
X_8 – moisture of crushed mass;
X_9 – presence of cascades on the sieve surface;
X_{10} – coefficient of the live section of the sieve;
X_{11} – sizes of particles entering the separation;
X_{12} – shape of sieve holes;

X_{13} – the nature of the supply of crushed mass.

The amount of mass supplied to the separation (X_4) does not depend on the design of the device and is regulated by the initial requirements for development. The material of the sieve (X_7) and the moisture content of the separated mass cannot be changed in the process of experimental research and operation of the technological equipment. The first indicator is embedded in the design of the separator, and the second depends on the conditions before crushing. The method of supplying the crushed mass to the sieve cannot have a significant effect on the injury of the seeds, because the seeds have a high resistance to the perception of static and shock loads. After the analysis of the importance and waste of insignificant factors, the diagram of ranks was built until their value decreases in proportion to the degree of influence of one or another factor on the quality of the technological process. Rank level values are placed against the background of the chart columns. The analysis of the results of the expert assessment and their statistical processing allows us to conclude that the factors X_1, X_2, X_3, X_5, X_6 have the greatest influence on the progress and quality of the technological process. Factors $X_9 - X_{12}$ can be rejected and excluded during further research using the theory of experimental planning.

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_1	-15	0	15	15	degree
X_2	100	300	500	200	1/s
X_3	10	30	50	20	mm
X_5	10	20	30	10	degree
X_6	1.0	1.5	2.0	0.5	m

In accordance with the experimental plan, an assessment of the dependence of technological process indicators on the frequency of vibrations of the sieve, the angle of its inclination, the amplitude of oscillations, the angle of addition of forced oscillations and the length of the separating surface, which have the greatest influence on the quality of the separator, was carried out. Repeatability of experiments for each of the optimization criteria – three times. In each line of the plan, the average value of DS, LS and PS was calculated. Experimental studies were carried out on seeds of cucumber (variety 'Konkurent') and melon (variety 'Ukrainka'). After statistical processing of experimental data, mathematical models describing the technological process were obtained.

3. Resource-saving method of extracting cucumber and melon seeds

There are presented the resource-saving method of extracting cucumber and melon seeds. It can be realized by the modernized construction of the cucumber and melon seeds separator the feature of which is the use of a two-screen sieve system. In the given system, the upper sieve separates the peel, and the lower sieve separates the seeds and pulp; the pulp and juice will be the by-product of the second sieve. The sieve, which performs an inertial movement, helps to extract the seeds associated with the peel. The technological scheme of extracting cucumber and melon seeds with experimental separator excludes stage of rubbing seeds that can prevent its damaging. The resource-saving method of extracting cucumber and melon seeds can help to reduce the amount of water needed for further washing of the seeds.

The separator is a system consisting of two sieves. With the help of the upper sieve, the coarse fraction of the crushed peel is separated, while the lower sieve separates the seeds. Other

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fractions fall into the tray, namely pulp, pulp particles and juice. In order to reduce the loss of seeds in the peel fraction, it is advisable to use the mode of the inertial separator. Carrying out additional friction of the material against the edges of the holes in the peel fraction reduces the seed content. The mode of the vibrating conveyor for the second sieve is used to increase the passage of pulp through the sieve openings. There is presented the structural scheme of the cucumber and melon seed separator designed for cleaning seeds from pulp and crushed peel particles (figure 2). The technological process is as follows: the fruits are loaded with a special conveyor into the hopper 2 of the grinding chamber 3. Crushed by drums 4; 5 mass enters the sieve 10. The dimensions of the cells of the upper sieve for cucumber 5x15 mm. On its surface, the crushed peel (over-sieve product) is removed from the technological zone. Seeds, pulp and small pieces of peel equal in size to the seeds (product of grating) fall on the surface of the sieve of the second sieve 11 with the size of the holes. Seeds with impurities on its surface are fed for further cleaning, and pulp, juice and other small impurities fall into the tray and from it into pump 4.

The following adjustments are provided in the separating device:

- the rotation frequency of the cranks and, therefore, the frequency of the sieves oscillations was changed by V-belt variators 19; 20;
- the angle of inclination of the grating was changed by adjusting the length of hinged suspensions of sieves 12; 13;
- to change the length of the working part of the separating part of the sieve, partitions were installed along the movement of the technological product.

There are presented technological schemes of extracting cucumber and melon seeds with basic and experimental separator (figure 3). The second scheme excludes stage of rubbing seeds that can prevent its damaging and allows to significantly reduce water consumption when washing seeds and achieve an improvement in the quality of the technological process.

4. Results

In the course of the research:

- the factors that have the greatest influence on the quality of the technological process and are most amenable to regulation have been identified;
- an experimental setup with variable gratings and the ability to adjust the main parameters is presented;
- experimentally investigated the dependence of seed purity (PS), its losses (LS) and damaging (DS) on the frequency and amplitude of vibrations of the sieve, the angle of inclination of the sieve and the angle of application of the vibration force, as well as the length of the working zone of the separator.

The frequency of sieve vibrations, the amplitude of sieve vibrations and the length of the sieve have the greatest impact on the quality of the technological process. This is evidenced by the largest value of the coefficients for these factors in the regression equations. By equating to zero the value of the angle of inclination of the sieve and the angle of application of the force, the regression equations have the form:

$$PS = 65.519 + 2.802X_2^2 + 1.852X_3^2 + 6.507X_2 + 3.573X_6 - 0.645X_2X_3 + 1.572X_2X_6 + 1.209X_3X_6 \quad (1)$$

$$DS = 4.252 + 1.788X_2^2 + 1.522X_3^2 + 2.155X_6^2 + +0.387X_3 + 1.487X_6 - 0.987X_2X_6 \quad (2)$$

$$LS = 6.013 + 0.993X_2^2 - 0.907X_6^2 - 1.38X_3 - 1.948X_6 + 0.493X_2X_3 \quad (3)$$

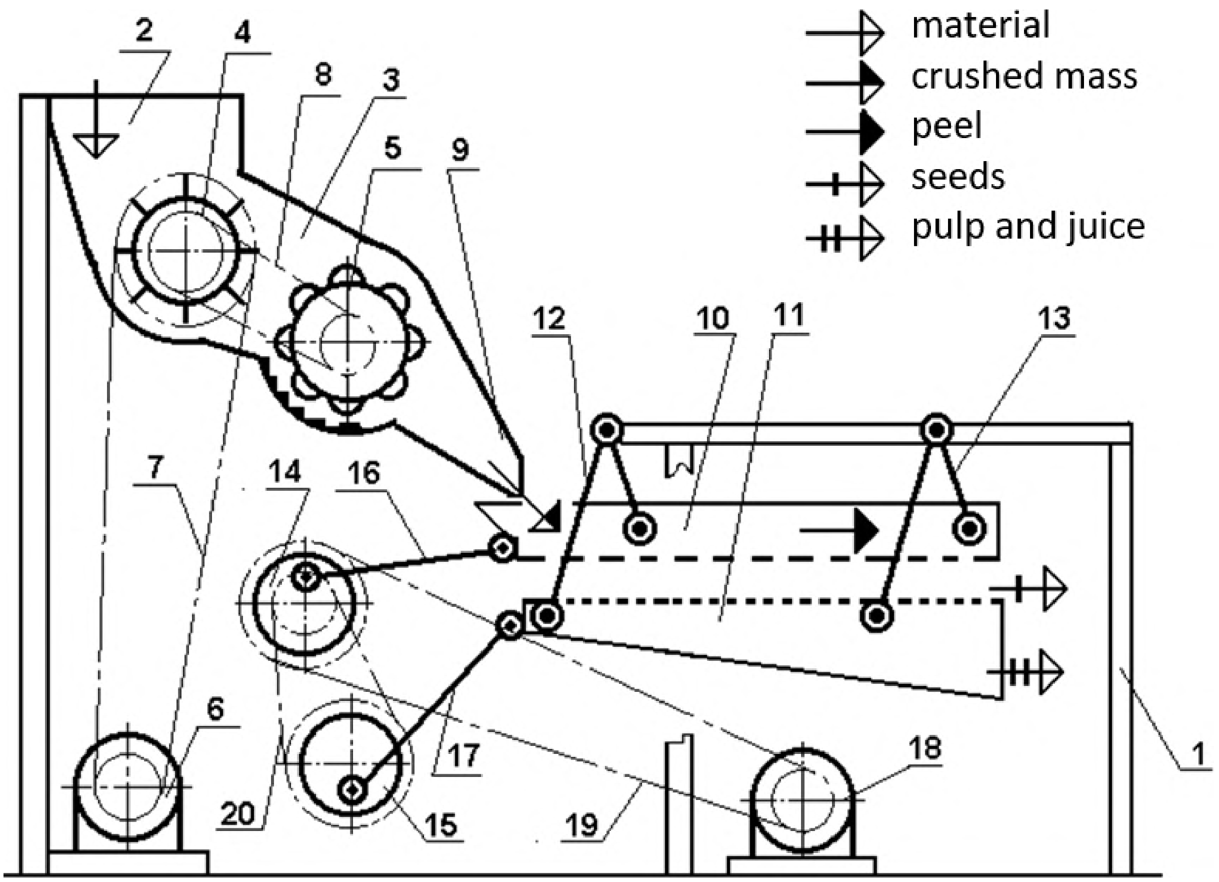

Figure 2. The scheme of the prototype of the cucumber and melon seed separator (1 – frame; 2 – receiving hopper; 3 – grinding chamber; 4 – grinding drum; 5 – wiping drum; 6 – electric motor; 7 – V-belt transmission; 8 – V-belt variator; 9 – tray; 10, 11 – the last grates; 12, 13 – sieves; 14, 15 – crank and connecting rod mechanisms; 16, 17 – hinged rods; 18 – electric motor; 19 – V-belt transmission; 20 – V-belt variator).

However, these equations are also not subject to canonical transformation, because they have an “extra” factor. It is equated $X_6 = -1$, after which the regression equations transform:

$$PS = 61.946 + 2.802X_2^2 + 1.852X_3^2 + +4.935X_2 + 1.209X_3 - 0.645X_2X_3 \quad (4)$$

$$DS = 4.929 + 1.788X_2^2 + 1.522X_3^2 + 0.987X_2 + 0.387X_3 \quad (5)$$

$$LS = 6.954 + 0.993X_2^2 - 1.384X_3 + 0.493X_2X_3 \quad (6)$$

Two-dimensional intersections of the response surfaces are presented.Having successively fixed both at the +1 level, and having performed calculations similar to the above, it is obtained the regression equation in the usual form with a new mutual combination of factors. When $X_2 = +1$, the regression equation takes the form (figure 4).

When setting the length of the sieve at the minimum level, it is impossible to achieve seed purity of more than 72%. The zone of optimal combination of factors is limited by the arcs of the HP curves; LS and DS intersecting at points I; II: III. At the same time, seed purity is within 71-72%; damaging will be less than 6%, and losses will not exceed 7%. For the vibration frequency of this technological mode is 24.3-36.25 (1/s), and the amplitude is 34-46 (mm). If the seed purity indicator drops to 71%, and losses to 8%, the range of permissible variation of

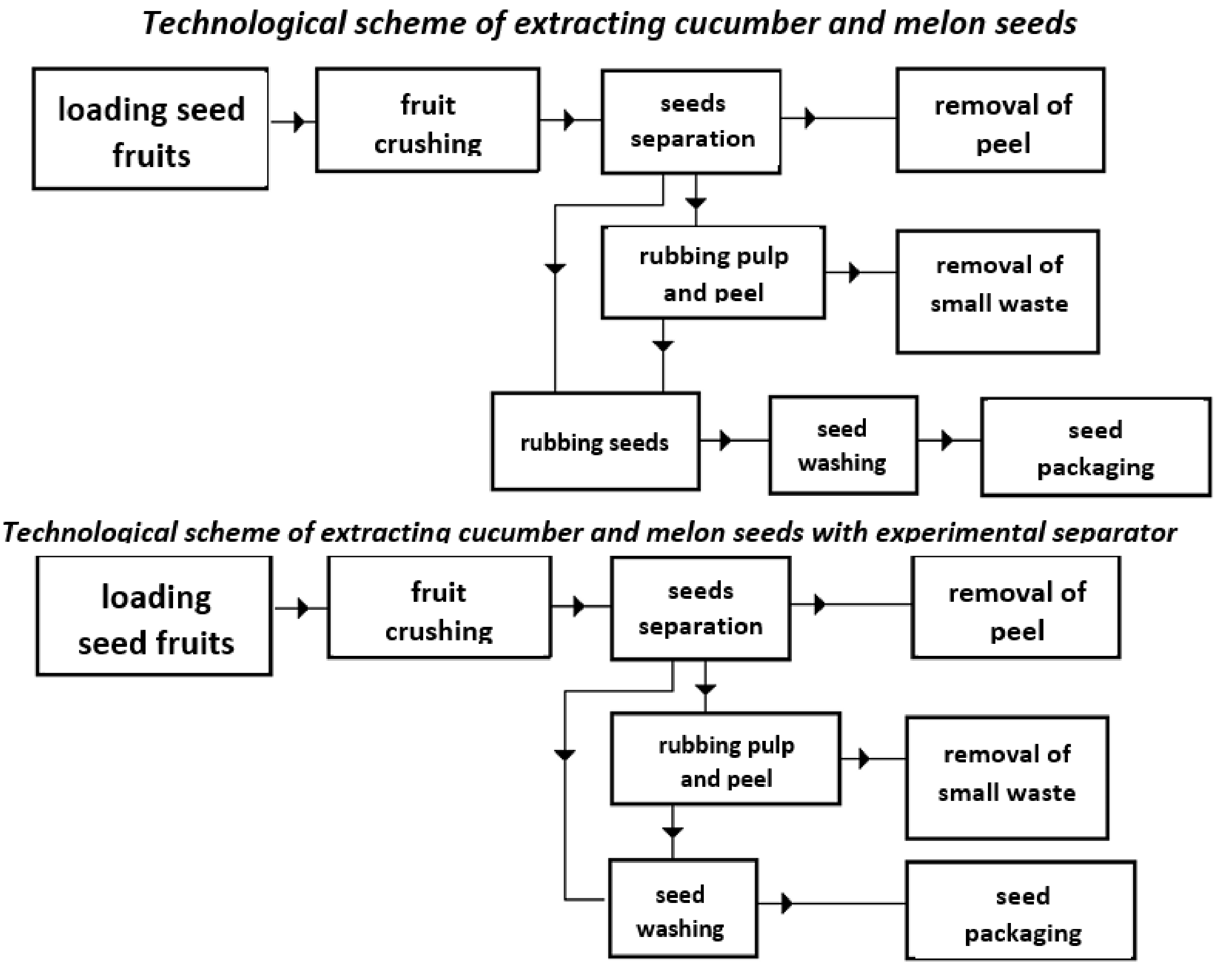

Figure 3. Technological schemes of extracting cucumber and melon seeds with basic and experimental separator.

kinematic modes (the figure is limited by points IV, V, VI) will be: for frequency – 24.3-45.0 (1/s); for an amplitude of 25-42 (mm).

Two-dimensional intersections of the response surfaces are shown in figure 5. Having successively fixed both at the +1 level, and having performed calculations similar to the above, it is obtained the regression equation in the usual form with a new mutual combination of factors.

When $X_2 = +1$, the regression equation takes the following form.

The analysis of the results of the experiment, the graphic interpretation indicates an increase in the indicators of the technological process when the frequency of oscillations is fixed at the maximum level. It was possible to achieve damage of seeds less than 4% with their purity more than 75% and losses in the range of 6-7% (the figure is limited to points I, II and III). The amplitude of oscillations is in the range of 24-32 mm, and the length of the working part is 1.51-1.625 m. In case of deterioration of damaging indicators to 5%, it is possible to achieve seed purity of more than 77.5% and losses do not exceed 6% (the figure is limited by points IV, V and VI). Independent factors can lie in the range: amplitude – 25-40 mm; sieve length – 1.75-1.825 m for a frequency of oscillations of 24.0-42.0 (1/s), for an amplitude of 24-48 mm.

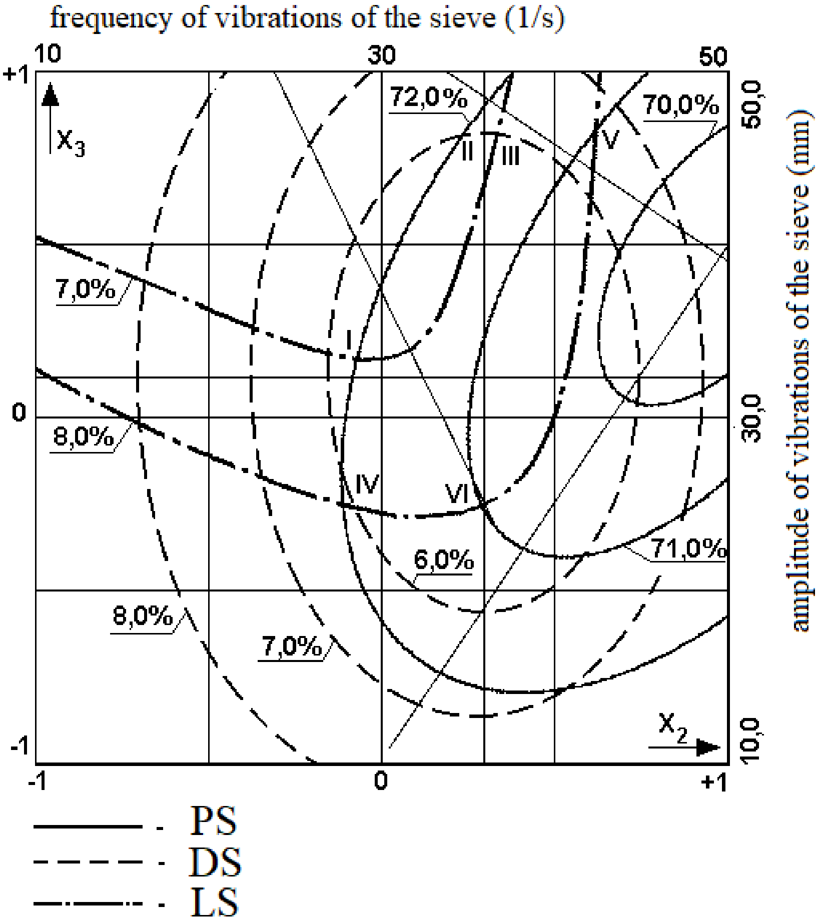

Figure 4. Two-dimensional intersections of response surfaces at $X_1 = 0; X_6 = -1; X_5 = 0$.

$$PS = 74.825 + 1.852X_3^2 - 0.645X_3 + +5.145X_6 + 1.209X_3X_6 \quad (7)$$

$$DS = 6.040 + 1.522 + X_3^2 + 2.155X_6^2 + 0.387 + +X_3 + 0.491X_6 \quad (8)$$

$$LS = 7.006 - 0.907X_6^2 - 0.891X_3 - 1.948X_6 \quad (9)$$

When $X_3 = +1$:

$$PS = 67.371 + 2.802X_2^2 + 5.865X_2 + +4.776X_6 + 1.572X_2X_6 \quad (10)$$

$$DS = 6.144 + 1.788X_2^2 + 2.155X_6^2 + 1.478X_6 - -0.987X_2X_6 \quad (11)$$

$$LS = 4.625 + 0.993X_2^2 - 0.907X_6^2 + 0.493X_2 - 1.948X_6 \quad (12)$$

Two-dimensional intersections of the response surfaces for the considered cases are shown in figure 6.

Analyzing the last graphic dependence, it can be concluded that in order to achieve the values of quality indicators of the technological process, which are comparable to the two previously considered options, it is necessary that the frequency of vibrations is 9.0-42.0 (1/s), and the length of the working part of the sieve is 1.2-1.6 m. The given combination of factors corresponds to the figure bounded by points II; III; IV, limited by the curves PS = 70%, DS = 6% and LS = 8%.

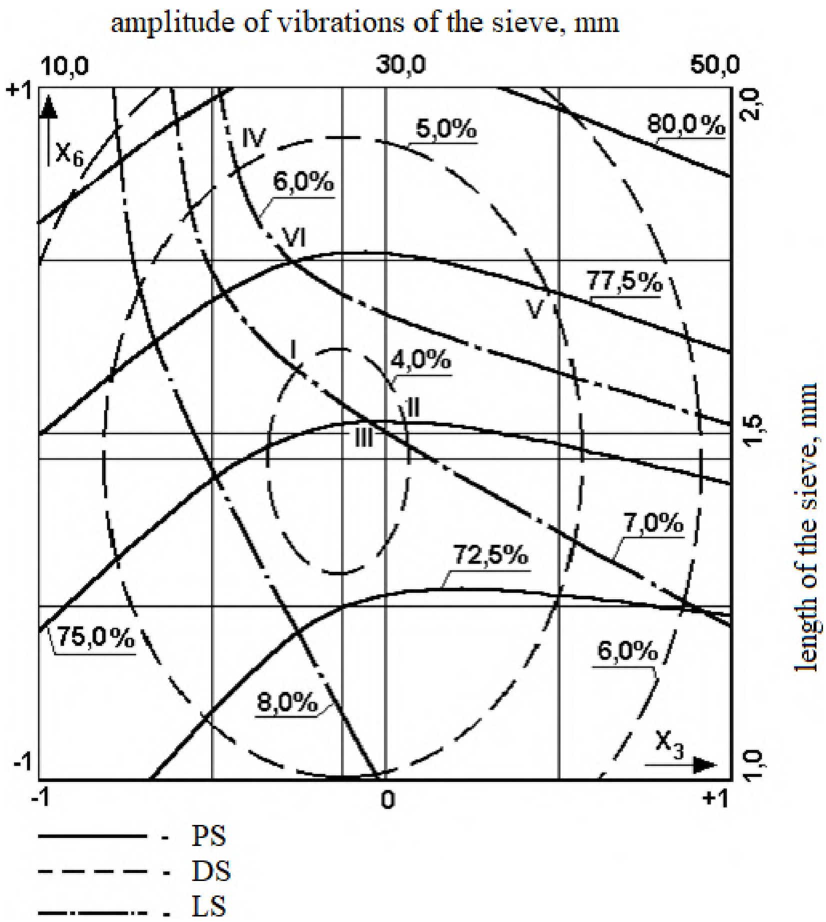

Figure 5. Two-dimensional intersections of response surfaces at $X_1 = 0; X_2 = +1; X_5 = 0$.

There are analyzed the graphical interpretation of the results of the experiment. Considering the constructed lines of “equal output”, can be concluded that the task of optimizing the main kinematic modes and design parameters is contradictory. An increase in any of the investigated factors: frequency of oscillations, amplitude of oscillations and length of the sieve leads to an improvement in the indicators of seed purity (PS) and their losses (LS), but to a certain extent worsens the indicators of damaging (DS).

5. Discussion

With the increase in the average annual air temperature on the planet and the aridity of the climate, their areas have a tendency to progressively expand. In the southern regions of Ukraine, zones of harmful agriculture are created due to the increased concentration of salts in the soil, which also suppresses natural flora and limits cultural diversity. The main reproductive organ of plants, the seed, is a unique product of evolution with a variety of morphological, physiological and biological characteristics, including different adaptability. Therefore, obtaining high-quality seeds and reducing resource costs for the technological process is an important task [26].

A lot of procedures in the technological processes are currently completed by people. Because of this, a big number of melon farms need a big amount of funding and human resources. Additionally, workers can measure the fertiliser solution incorrectly or fail to prepare the water and fertiliser solution needed for each planting step. The entire melon plant may be impacted by this and suffer harm as a result. Furthermore, low- to middle-class farmers who cannot

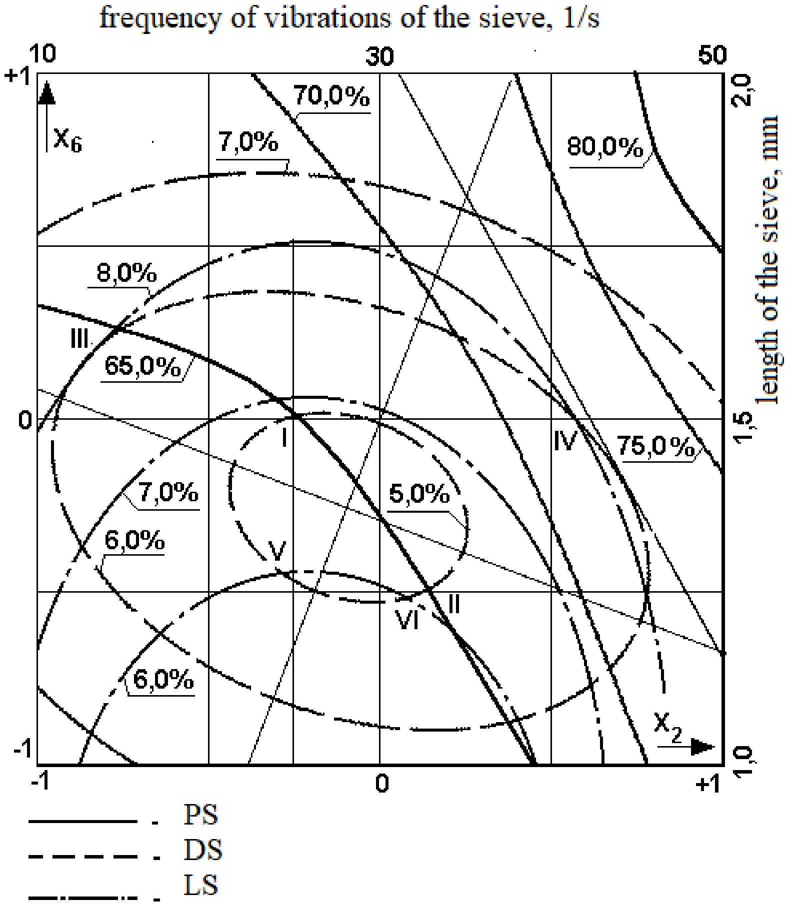

Figure 6. Two-dimensional intersections of response surfaces at $X_1 = 0; X_3 = +1; X_5 = 0$.

afford to make large investments in sophisticated machinery operate the majority of small and medium-sized melon fields [27].

A scientific notion of microwave energy's influence on grain crop growth rate under significant chemical reactant reduction was developed through systematic joint experiments conducted in both laboratory and field settings. A technique for treating vegetable crops' seeds that guarantees development rate has been devised; this is crucial for greenhouse vegetable farming. The findings that the microwave treatment increased the germination rate of melon seeds from 10% to 83% are interesting from a practical standpoint [28].

Energy-efficient agricultural equipment of low-productivity enterprises, according to its design, allows to use a simple technological scheme and reduce energy and resource costs for the technological process in the context of use in sustainable food systems [29].

From the analysis of previously conducted studies, it was established that determining the optimal relationship between the structural and kinematic parameters of separating devices of any type is a rather difficult task. In order to reduce the volume of experimental research, reduce the number of adjustments of the laboratory installation, the number of its working organs, as well as to obtain objective information about the dependence of seed injury, their purity and the amount of losses from the simultaneous change of several kinematic modes. Industrial machine models built for intricate production process automation and mechanisation are necessary for the growth of vegetable and melon seed production. Enhancing and growing the seed production sector will contribute to ensuring that agricultural production has access to seeds produced on-site, which will cut costs and boost industrial productivity. If growers of vegetables and melons generate their own seeds, they can lower the cost of producing these crops.

Vegetable and melon seeds are commonly separated using vibrating machinery. Chen and Yan [30] present their investigation on simulating crop sieving at varying vibration amplitudes, frequencies, and angles. The findings indicate that the sieving efficiency is not significantly affected by the vibration direction's angle of departure. The sieving efficiency rises and subsequently falls as other factors are taken into account. With an amplitude of 4 mm, a vibration frequency of 13 Hz, a sieve angle of 8°, and a vibration direction angle (angle between the vibration line and the Z-axis) of 0°, the optimal combination of sieving parameters was discovered after analysing the data. As in the case of the suggested design solution, the combination of vibration and inertial motion has a favourable impact on the quantitative and qualitative markers of seed separation [30].

The practical use of imbalanced vibration drives in adjustable drives of vibrating sieves has been investigated [31]. Both the operation of vibrating screens in the so-called "superresonant" mode and frequency control of the exciting force of the vibration motors are necessary for synchronous operation. The most significant experimental findings that were acquired under actual working settings are presented in this paper together with an experiment to ascertain the amplitude-frequency characteristics of vibrating screens. The authors' design strategy, which maximises design and operating parameters through the use of graphs, allows for a decrease in losses and an increase in seed yield [31].

For the goal of sorting seeds, Kaliniewicz et al. [32] assessed the correlations between the primary physical characteristics of seeds from a chosen species. Five species' seeds were examined for physical characteristics, and correlation and regression analysis were used to establish whether these features were interrelated. Sorting seeds using a sieve with two or more screens is recommended. The study highlights the necessity of technology tools for farms to process agricultural produce after harvest, with vibration machines being especially useful in this regard. By using the suggested design approach, high-quality seed separation is ensured by additional work in the inertial mode in addition to the use of vibrating machine properties [32].

The best values for the design and operational parameters of seed separators can be found by simulating the technology of processing the seed mass of vegetable and melon crops [33]. The researchers offered a solution to the seed characteristic prediction challenge. The final material's purity and seed loss were the optimisation criteria. On the other hand, compared to vibrating equipment, the pressurising machine employed in the experiment produced less-quality seed separation. Furthermore, the proposed study of the movement of the technological mass of vegetable and melon seeds allows for the optimal operating modes of the separator to be chosen using the suggested graphs, whereas the mathematical modelling of the technological process is time-consuming, only allows for modelling a specific sample of varieties of vegetable and melon crops, and does not allow for the prediction of the results [33]. As demonstrated by the experimental data gathered based on the mechanical and technological characteristics of the chosen samples, the combination of inertial and vibration motion of the sieves is the benefit of utilising the suggested design solution for the separator. It is possible to reduce the amount of water needed for seed washing and improve the level of the technological operation by using a resource-saving method of extracting cucumber and melon seeds.

6. Conclusion

The lack of modern, highly productive equipment does not allow to fully realize the possibilities in providing agriculture with its own seeds of cucumber and melon. The purchase of seeds leads to additional expenses, reduces the productivity of open ground melon cultivation due to the fact that not all varieties are regionalized. There are studies on the substantiation of the design parameters and kinematic modes of seed separators from the crushed peel and pulp obtained in the process of crushing seed fruits. The conducted theoretical justification applies only to sieve-type separators with a horizontal sieve with reciprocating movement and constant pressure of particles of crushed mass on the surface of the sieve.

Using the proposed method of extracting cucumber and melon seeds allows to lower the amount of water used for seed washing and raise the standard of the technological procedure. The feature of the proposed design solution of the separator of the melon and cucumber seeds is that the upper screen operating in the mode of an inertial separator and the lower screen operating in the mode of a vibrating separator that promotes better separation of seeds. The upper screen separates the coarse fraction of the crushed peel, while the lower screen separates the seeds. The remaining fractions, such as pulp, pulp particles and juice, fall into the tray. To reduce seed losses in the peel fraction, it is advisable to use the inertial separator mode. Additional friction of the material against the edges of the holes in the peel fraction reduces the seed content. The mode of the vibrating conveyor for the second sieve is used to increase the passage of the pulp through the sieve holes.

Factors affecting the quality of the technological process of the proposed solution of the cucumber and melon separator were identified: the angle of inclination of the sieve surface, the frequency of oscillations of the sieve, the amplitude of its oscillations, the angle of application of the vibration force and the length of the sieve. The following optimization criteria were chosen: purity of seeds, the extent of their damage and the level of seed losses. The factors that have the greatest influence on the quality of the technological process have been established: the frequency of vibrations of the screen, the amplitude of vibrations and the length of the working surface of the sieve. At the same time, the ranges of variation of independent factors made it possible to ensure modes of both inertial separation and vibration separation. The ranges of the optimal combination of independent factors are as follows: in case of seed injury 4-6%, purity 70-75%, losses are within 6-7%, a necessary condition is the frequency of oscillations 9.0-42.0 (1/s), the amplitude oscillations of 24-32 mm, and the length of the working part sieve 1.2-1.6 m. In the vibroseparation mode (oscillation frequency more than 30 (1/s); amplitude more than 35 mm (with an angle of application of the vibration force of 10°) seed damage does not exceed 5%, and their frequency is within 70...71%. At the same time in the inertial mode separator, seed loss at the level of 5-6% is achieved. Prospects for further research are recommendations on the design schemes of separator, its kinematic modes, which allows to intensify the process of cleaning freshly separated wet seeds from organic impurities.

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Assessment of trends in the functioning of the grain industry of the EU countries using ARDL modeling

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Assessment of trends in the functioning of the grain industry of the EU countries using ARDL modeling

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Abstract. The application of ARDL modeling at the macroeconomic level for the analytical description and analysis of dependencies of production productivity in the grain industry on natural-climatic, technical-technological and marketing factors is studied. It is determined that the construction of the production function for the agrarian sector determines the consideration of internal and external factors of the organization of production and the conditions for its conduct. Another difficult point is the asynchrony of the dynamics of prices for grain and production resources, which necessitates bringing the indicators of costs and output to a comparable form, which determines the artificiality of comparison and non-stationarity of the dynamic series included in the model. It has been proven that the means of overcoming these obstacles is the application of the dependent lag autoregressive model (ARDL). The non-equivalence of the influence of individual factors on the dynamics of yield has been established. In particular, the p-value at the level of one percent has the payback of costs for the production of soft wheat grain in the reporting year, its first and third lag, as well as the second and third lag of payback of costs for the production of durum wheat. At the same time, there is an alternation of the sign of regressors, due to a decrease in prices in years of excess grain production and their increase in lean years. Likewise, the value of the unit cost regressor is also negative, while their lags according to the AIC criterion were not included. The prerequisite for this is the industrial nature of the technologies used. Thus, with an average yield of about 70 c/ha, the variation of the latter over the 29 years of the study did not exceed 7%, and therefore the increase in unit costs, and, accordingly, the yield, but does not provide a simultaneous increase in income due to a decrease in prices. In view of this, a negative value is logical cost regressor. Under such conditions, further study of the prerequisites should be aimed at studying the behavior of lag values of costs and the impact on their formation of a common European policy of regulating the productivity of agricultural production.

1. Introduction

Regression modelling is traditionally used to evaluate the efficiency, planning and forecasting of agricultural production. Multiple regression, discriminant, factor, cluster and logistic regression analysis, and principal component analysis are widely used in modelling the performance of the agricultural sector. Unfortunately, the accuracy of forecasts is sometimes significantly affected by the multicollinearity of indicators, their autocorrelation in certain years, and extreme structural shifts. These factors can reduce the adequacy of regression models and their parameters obtained using the least squares method (*OLS - Ordinary Least Squares*) [1]. At the same time, since the results of production in crop production are influenced by a significant number of interrelated factors with their inherent multicollinearity, it is advisable to use other approaches, in particular, an autoregressive model with a distributed lag (*ARDL – Autoregressive Distributed Lags*).

This model is a traditional OLS regression in which the independent variables are the lags of the factor variables and the outcome variable [2]. The ARDL, known for several decades, began to be widely used to study the cointegration of economic indicators after the publication of the works of Pesaran and Shin [3, 4]. Cointegration is defined as the property of several non-stationary (integrated) dynamic series to have some stationary linear combination [5]. Cointegration is inherent in many economic indicators, and its manifestation is that despite the random (poorly predictable) nature of simultaneous changes, there is a long-term relationship between them that causes common, interrelated fluctuations. In fact, we are talking about the Error Correction Model (ECM) – when short-term changes are corrected depending on the degree of deviation from the long-term trend.

The works of Engle and Granger [6], Johansen and Juselius [7], Saikkonen and Lütkepohl [8] are devoted to cointegration methods, but the advantage of ARDL is the possibility of including non-stationary variables in the model [9]. This model is based on a single equation, which allows the use of a sufficient number of lags [10]. At the same time, the number of estimated parameters decreases [3], and therefore ARDL is more reliable for samples of 30-80 observations [11–13], while Johansen's cointegration test requires at least 100 observations [14]. The ARDL method reflects the delayed effect of the aftereffect of the factor (x) and dependent (y) variables, as it includes their lags, which are taken into account in serial correlation [9]. In this case, the dynamic error correction model (ECM) can be derived from the ARDL using a linear transformation [15], which allows integrating short-term dynamics with long-term equilibrium without losing long-term information.

Therefore, taking into account the growth in demand for food products, research and development of methodical approaches to modeling macro- and microeconomic processes in the agricultural industry using ARDL-modeling is of particular importance.

2. Theoretical background

The use of dynamic models to describe the relationship between indicators of economic processes is based on the assumption of the presence of a long-term equilibrium relationship in changes in these indicators. A dynamic model is characterized by a dynamic relationship between the behavior of a variable at a current point in time, which may have an impact on it or on other variables in future periods, and these effects are usually inertial in nature [16]. The most common approach to the formalization of dynamic relationships is to use the resulting indicator as an independent lag variable simultaneously with the variables that characterize the process in the current period:

$$y_t = f(y_{t-1}, x_t), \tag{1}$$

where y_t and x_t are the values of the dependent and independent variables in the current period, y_{t-1} is the value of y in the previous period.

If the variable y is a function of the current and past values of the independent variable x, then it is a dynamic model with a distributed lag, in which the influence of the independent variable (x) on the dependent variable (y) can be traced in dynamics. The influence of the dynamics of the factor variable can be traced both at the present moment and in the future, and therefore the consequences of today's management decisions can affect the results of production both in the current, and in subsequent periods. For example, the hereditary effect of fertilizers has been observed for several years, and therefore managers are interested not only in the impact of changes in costs on the yield of the product, but also in the time during which the hereditary effect will be prevented. In view of this, it is expedient to introduce into the production function the values of the factor variable for several previous periods (lags):

$$y_t = f\left(x_t, x_{t-1}, x_{t-2}, \dots x_{t-k}\right), \tag{2}$$

where x_{t-1} and x_{t-2} are the values of the variable for the two periods (lags).

After combining (1) and (2), we get a dynamic model with lag variables (x) and (y):

$$y_t = f\left(y_{t-1}, x_t, x_{t-1}, x_{t-2}\right). \tag{3}$$

It is a distributed lag autoregression (ARDL), i.e. an extension (2). It is generally accepted that a change in one economic variable can affect another with a certain delay, as a result of which these changes do not occur instantaneously, but over several periods. So, we have a distributed model with infinite lag, in which autoregression (AR) characterizes the effect of its lags on the resulting function, and the component (DL) of the reflection is the lagging effect x. It can be described as follows:

$$y_t = \vartheta + \alpha_0 y_{t-1} + \ldots + \alpha_p y_{t-p} + \beta_0 x_t + \beta_1 x_{t-1} + \ldots + \beta_q x_{t-q} + e_t, \tag{4}$$

where p is the number of lags for y (lag order for y) and q is the number of lags for x (lag order for x).

Or in a more concise form of ARDL:

$$y_t = \vartheta + \sum_{i=1}^{p} \alpha_i y_{t-1} + \sum_{i=1}^{q} \beta_i x_{t-1} + e_t, \tag{5}$$

It assumes the presence of one explanatory variable, but if their number increases, ARDL (p, q_1, q_2, ..., q_k) will look like this:

$$y_t = \vartheta + \sum_{i=1}^{p} \alpha_i y_{t-1} + \sum_{i=1}^{q1} \beta_i x_{1t-1} + \sum_{i=1}^{qk} \beta_i x_{kt-1} + e_t, \tag{6}$$

This model is used to solve the sequential correlation problem to produce a transformed model with uncorrelated errors.

In turn, Pesaran et al. [4] proved that the error-corrected ARDL model looks like this:

$$\begin{gathered}\Delta y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_{1i} \Delta y_{t-i} + \sum_{i=1}^{q1} \alpha_{2i} \Delta x_{1t-i} + \ldots + \\ + \sum_{i=1}^{qk} \alpha_{(k+1)i} \Delta x_{kt-i} + \beta_1 y_{t-1} + \beta_2 x_{1t-1} \ldots + \beta_{k+1} x_{kt-1} + \varepsilon_t,\end{gathered} \tag{7}$$

where β_i (i=1, 2, ..., k+1) is the corresponding long-term relation, while the parameter α_i (i=1, 2, ..., k+1) is the short-term dynamic coefficient of the underlying ARDL model.

The main areas of application of ARDL are forecasting and multiplicative analysis [16]. Both are tools of economic policy and operational management, since forecasting economic variables is a key issue for economists, and multiplicative analysis evaluates the effect on the behavior of one independent variable of others and the time limits of their influence.

3. Literature review

Issues of cost efficiency are usually studied through the prism of production functions of production of socially significant products. It should be noted the works devoted to the study of production functions, in particular pray, which focus on determining the forms of the production function adequate to economic processes [9, 17–23]. Attention is drawn to studies in which production functions are used to assess productivity, returns to scale and price in industry, trade and international economic relations [20, 24–32]. A significant number of works are devoted to the development of methods for assessing multi-product production functions [28, 33–36].

A whole direction of macroeconomic research, starting with the work of Hall [37], is devoted to the uncertainty of product prices. At the same time, most studies, highlighting the instrumental features of OLS functions, leave out the dynamic aspects of modeling at the level of an economic entity. For example, a number of publications are devoted to dynamic ARDL-modeling the relationship between macro-financial and macroeconomic indicators. Thus, Ghavam Masoodi and Tashkini [38] uses his study of the long-term relationship between the inflation rate and its factors. Tian and Ma [39] examines the relationship between the exchange rate and the stock market. Chaudhry et al. [40] examines the relationship between foreign exchange reserves and inflation rates in Pakistan. Chou and Tseng [41] analyzes the relationship between oil price volatility and inflation in Taiwan.

Some authors are trying to expand the ARDL toolkit. Thus, Alimi [42] investigated the relationship between inflation and interest rates in Nigeria and the degree to which the Fisher effect is fulfilled. He applied ARDL testing and vector error correction (VECM), and tested the stability of the function using CUSUM and CUSUMSQ. Hove and Tursoy [43] established a long-term relationship between stock prices and domestic interest rates in Turkey's financial markets. The study relied on the ARDL and the Vector Autoregressive Cointegration. Equations based on the modified least squares method (FMOLS), dynamic least squares method (DOLS), and regression (CCR) were applied to test long-term elasticity. Moawad [44] used ARDL to investigate the relationship between financial sector development and economic growth in France and Malaysia.

ARDL at the microeconomic level was applied by Blundell and Bond [19], who focused on the application of ARDL models for panel data. The focus was on single-equation models with dynamic autoregression and explanatory variables that are endogenous (not strictly exogenous), as well as estimates of the Generalized Method of Moments (GMM). The paper considers a simple autoregressive model for the rate of investment and the main production function for an industrial enterprise. At the same time, Chandio et al. [45] applied ARDL modeling to analyze production processes in agricultural formations. It investigated the impact of support prices on wheat production in Pakistan in 1971-2016. and confirmed their positive long-term impact, as well as fertilizer application, on wheat production using.

Therefore, today there is a need to deepen research on the possibilities of using ARDL for modeling at the level of agricultural enterprises, to improve approaches to the interpretation of the essence of lags of factor and resultant indicators, in particular, the use of this approach in forecasting the results of crop production.

4. Purpose, data and methodology of the study

The aim of the article is to highlight the results of the study of the use of ARDL modeling at the macroeconomic level for the analytical description and analysis of dependencies of production productivity in the grain industry on natural-climatic, technical-technological and marketing factors.

The basic production function is a model that describes the relationship between the accumulation of resources, their consumption and output:

$$y_t = f\left(x_{t1},\ x_{t2,} \ldots x_{tk}\right), \tag{8}$$

where y_t and x_{t1}, x_{t2}, x_{tk} are the values of the resulting feature and its regressors in the period t.

For the production of wheat grain, the outputs are output in physical or cost terms, and the inputs are consumed resources (resource potential), operating costs, or both. At the same time, the most important of them is soil fertility. But its inclusion in the model is problematic given the complex nature of the concept, and reduction to an economic equivalent causes a number of assumptions, which complicates the model itself and reduces the quality of the forecast. The analysis of publications shows an increase in attention to the economic assessment of land resource potential and its impact on production results. Unfortunately, the instrumental aspects of its process are not addressed.

The proposed approach is based on the assumption that the resource potential in conjunction with the production technology are components of the production potential of the agricultural sector, the efficiency of which is characterized by the culture of agriculture. At the same time, it is directly reflected in the yield for several periods preceding the reporting one, which determines its use in the autoregressive production function (AR).

Another disadvantage of agrarian production functions is the mutual correlation of certain types of costs, due to their synchronous growth as technology becomes more complex. In addition, traditional production functions almost do not take into account the aftereffect of fertilizers, in particular phosphate fertilizers, and the application of organic fertilizers has a positive effect on soil fertility, which causes mutual correlation of fertility indicators and the costs of their increase and complicates the formalization of the production function. At the same time, due to the aerobiological nature of the not always strictly functional, but nevertheless tangible relationship between production costs and output to overcome the problem of multicollinearity, a multifactor cointegration ARDL model can be applied, which will allow to assess the degree and speed of formation of the multiplier effect and correction of market failures through the prism of changes in the level of unit costs.

At the same time, a prerequisite for modeling is the feedback of input output, i.e. indicators of technological and economic efficiency on costs. In market conditions, such a factor is the price. At the same time, if its individual value is an assessment of the manufacturer's competitive position, then the average value is a factor in adjusting unit costs, which causes an increase (decrease) in productivity in the next period. Therefore, on a par with the lag values of yield and costs to ARDL It is advisable for the model to include sales price lags.

4.1. Inventory statistics

Turning to the results of the study, it should be noted that given the inflationary nature of prices for purchased resources, the inclusion of costs per unit of crops without pre-treatment leads to erroneous conclusions, and therefore the dynamics of costs was brought to a comparable type. Due to the conditions of the war, the possibilities of its implementation according to the data of Ukrainian agricultural formations are limited, and therefore the indicators of EU farms were used. In particular, data on the unit costs of wheat grain production at constant prices in 2010 of French agricultural formations are available on the Eurostat (ESS) website.

The European practice of statistical accounting provides for the independent accumulation of data on prices for durum and soft wheat grains, which is due to the different functional purposes of the products. Unfortunately, the inclusion of both prices in the model causes a deterioration in its quality due to the integration of their dynamic series at level $I(2)$ as a result of structural changes caused by the reform of the EU Common Agricultural Policy during the study period. In view of this, the dynamic price series were has been replaced by derivative indicators of payback of costs for the production of soft and durum wheat, which are reliable determinants of the costs of the current period.

Thus, the model included indicators of yield (YLD), production costs in constant prices (UVC), payback of costs for production and marketing of soft wheat *(PLSW)* and durum varieties ($PLDW$). Descriptive statistics of these dynamic series (table 1) and their graphical interpretation (figure 1) show a tendency to increase the return on costs for the production of durum wheat grain and the stationarity of other series. At the same time, against the background of a high variation in the indicator of costs in constant prices and their payback during the production of durum wheat grain, for yield and cost recovery, the production of soft wheat grain is moderate, which positively characterizes the common agricultural policy of the EU countries, which does not allow a crisis of overproduction.

Table 1. Basic inventory statistics (based on `https://ec.europa.eu/eurostat` data).

Variable	Abbreviation	Average	Standard deviation	Max	Min
Wheat yield, c/ha	YLD	68.8207	4.7951	74.9858	56.2021
Production costs per 1 ha of wheat crops, EUR*	UVC	11.0859	1.4916	15.2066	8.5323
Recoupment of costs for the production and sale of wheat grain					
soft varieties	$PLSW$	0.9094	0.0705	1.0464	0.7933
durum grades	$PLDW$	1.2320	0.1627	1.5387	0.9321

* in constant 2010 prices.

Attention should be paid to the positive correlation between each pair of independent variables. In particular, there is a low value for production costs and profitability of production and marketing of durum wheat, moderate profitability for production costs and profitability for the production and sale of soft wheat, and profitability for the sale of durum and soft wheat. The results of correlation analysis indicate the absence of multicollinearity between the independent variables, since all correlation coefficients are less than 0.8 (table 2).

Table 2. Correlation matrix of independent variables (based on `https://ec.europa.eu/eurostat` data).

	UVC	$PLSW$	$PLDW$
UVC	1.0000	0.2855	0.0203
$PLSW$	0.2855	1.0000	0.4651
$PLDW$	0.0203	0.4651	1.000

The next step was to check the rows for stationarity. A series is considered to be stationary if the mean, variance, and structure do not change during the study period. The stationarity test proposed by Dickey and Fuller [46] is based on the fact that the nonstationary series (X) is integrated in the d-order and has as many unit roots as many times as it needs to be differentiated

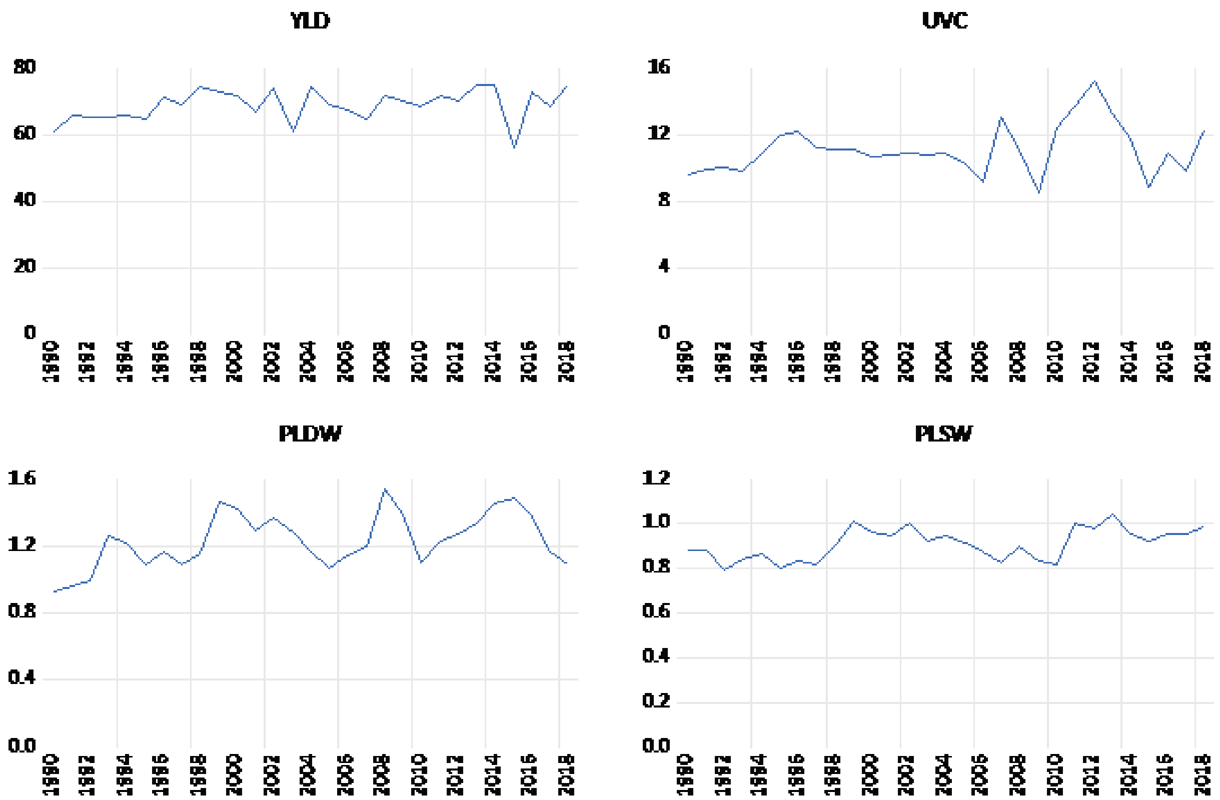

Figure 1. Dynamics of dependent and independent variables in 1990-2018 (based on `https://ec.europa.eu/eurostat` data).

to become stationary. Null hypothesis (*H0)* of the Dickie-Fuller test (*DF*) is the assumption that "the series has a unit root" versus the alternative hypothesis (*H1*) that it is stationary. The *DF* test assumes the presence of "white noise", so the autocorrelation of the dependent variable, which causes the autocorrelation of the error (ε) and the unreliability of the DF test. The ADF test for the variables included in the model showed that the dynamic series of yield and profitability of durum wheat are stationary at the *I(0)* level. On the other hand, the series of production costs per 1 ha of wheat crops and the profitability of sales of soft wheat varieties are integrated in the first order *I(1)* (table 3).

Table 3. Dickie-Fuller advanced test results (ADF) (based on `https://ec.europa.eu/eurostat` data).

Variable	Level of integration
YLD	*I(0)*
UVC	*I(1)*
PLSW	*I(1)*
PLDW	*1(0)*

5. Evaluation and specification

The specification of the proposed ARDL model is based on its canonical form, based on the results of research by Pesaran et al. [4]:

$$\Delta YLD_t = \alpha_0 + \sum_{i=1}^{p} \alpha_{1i} \Delta YLD_{t-i} + \sum_{i=1}^{q1} \alpha_{2i} \Delta UVC_{t-i} + \sum_{i=1}^{q2} \alpha_{3i} \Delta PLSW_{t-i} +$$

$$+ \sum_{i=1}^{q3} \alpha_{4i} \Delta PLDW_{t-i} + \beta_1 YLD_{t-1} + \beta_2 UVC_{t-1} + \beta_3 PLSW_{t-1} + \beta_4 PLDW_{t-1} + \varepsilon_t). \quad (9)$$

In the context of the existence of a long-term relationship, a conditional autoregressive model with a distributed lag is formed, which will allow estimating the coefficient of the long-term relationship:

$$\Delta YLD_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i YLD_{t-i} + \sum_{i=1}^{q1} \beta_i UVC_{t-i} + \sum_{i=1}^{q2} \theta_i PLSW_{t-i} + \sum_{i=1}^{q3} \gamma_i PLDW_{t-i} + u_t \quad (10)$$

In this case, the long-term equation is as follows:

$$YLD_t = a_0 + b_1 UVC_t + b_2 PLSW_t + b_3 PLDW_t + u_t \quad (11)$$

Thus, the long-term parameters in (11) can be obtained using OLS (10):

$$\overline{a}_0 = \frac{\alpha_0}{\left(1 - \sum_{i=1}^{p} \overline{\alpha}_i\right)}; \overline{b}_1 = \frac{\sum_{i=0}^{q1} \overline{\beta}_i}{\left(1 - \sum_{i=1}^{p} \overline{\alpha}_i\right)}$$

$$\overline{b}_2 = \frac{\sum_{i=0}^{q2} \overline{\theta}_i}{\left(1 - \sum_{i=1}^{p} \overline{\alpha}_i\right)}; \overline{b}_3 = \frac{\sum_{i=0}^{q3} \overline{\gamma}_i}{\left(1 - \sum_{i=1}^{p} \overline{\alpha}_i\right)}. \quad (12)$$

The second step of limit testing is to evaluate the conditional ECM, which is defined by the equation:

$$\Delta YLD_t = \alpha_0 + \sum_{i=1}^{p} \alpha_{1i} \Delta YLD_{t-i} + \sum_{i=1}^{q1} \alpha_{2i} \Delta UVC_{t-i} +$$

$$+ \sum_{i=1}^{q2} \alpha_{3i} \Delta PLSW_{t-i} + \sum_{i=1}^{q3} \alpha_{4i} \Delta PLDW_{t-i} + \upsilon ECT + \varepsilon_t, \quad (13)$$

where ECT is the error correction term, which indicates the rate of correction of the parameter, ECT shows how much of the disequilibrium is being corrected, i.e., to what extent any disequilibrium in the previous period is corrected in the current period.

6. Empirical results

During the analysis of the initial data in the EViews 12 software environment, the ARDL model with the lowest AIC value with a three-year yield lag, four-year lags of payback of costs for the production of durum and soft wheat grain was chosen as the baseline. On the other hand,

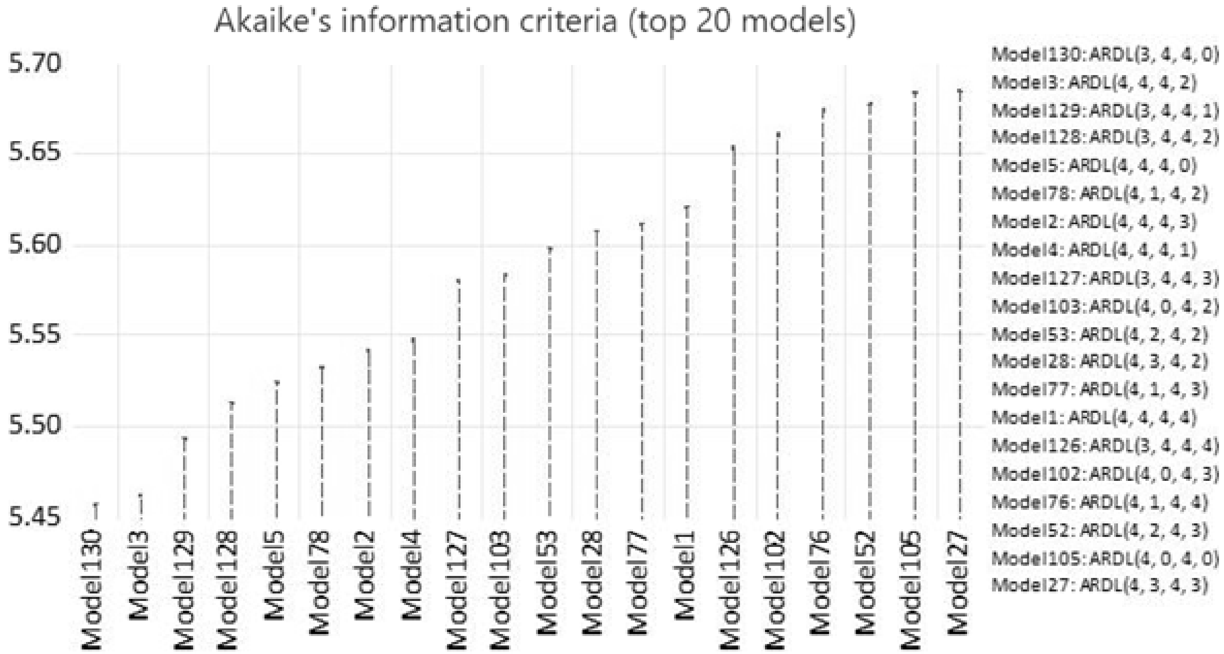

Figure 2. Summary graph of model selection (based on `https://ec.europa.eu/eurostat` data).

according to the chosen criterion of information similarity, the inclusion of lags of production costs per unit of crops in constant prices in 2010 is inexpedient, which requires additional research (figure 2).

The results of the simulation indicate discrepancies in the influence of lags of individual variables on the dynamics of yield (table 4).

In particular, the p-value at the level of 1% had the fourth lag of payback of costs for the production of durum and soft wheat, as well as the constant (α_0). The significance at the level of up to 5% was the first lag of yield and the second lag of payback costly production of durum wheat. In turn, the current costs per unit of crops at constant prices in 2010, the second and third lags of yield. The first and third lags of payback of costs for the production of durum wheat grain, the second and third fourth lags of cost recovery for the production of soft wheat grain were significant at the level of 10%. On the other hand, the indicators of payback of costs for the production of soft wheat grain in the reporting year and its first lag are not significant.

6.1. Bound test

The next step was the limit test for the presence of a long-term connection. It was found that the value of the F-statistic exceeds the upper limit for *I(0)*, based on this, it should be noted that there is a long-term relationship at the significance levels of 1%, 5% and 10% (table 5).

In view of this, an error correction model (ECM) was formed, which allows to assess which part of the disequilibrium is corrected, that is, how much the disequilibrium of the previous period is corrected in the current one (table 6).

It is recognized that a positive ECT coefficient indicates a recession, and a negative ECT indicates convergence. If it is equal to one, then during the period 100% of the deviation is corrected and the adjustment is instantaneous and complete, if ECT = 0.5, then 50% of the adjustment occurs in each period (year). ECT = 0 indicates that no adjustment occurs and it cannot be said that there is a long-term relationship. For the analyzed ECT model is negative

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Table 4. Model results ARDL(3,4,4,0) (based on `https://ec.europa.eu/eurostat` data).

Variable	Factor	Standard error	T-test	p-value
YLD(-1)	-0.5851	0.2311	-2.5317	**
$YLD(\text{-}2)$	-0.4062	0.2365	-1.7171	*
$YLD(\text{-}3)$	-0.4750	0.2274	-2.0887	*
$PLDW$	15.0995	9.6570	1.5636	*
$PLDW(\text{-}1)$	-16.3706	11.3606	-1.4410	*
$PLDW(\text{-}2)$	29.9923	12.6404	2.3727	**
$PLDW(\text{-}3)$	-18.5616	11.0300	-1.6828	*
$PLDW(\text{-}4)$	29.4581	10.4104	2.8296	***
$PLSW$	14.8728	19.8189	0.7504	doesn't mean.
$PLSW(\text{-}1)$	28.6199	24.0220	1.1914	doesn't mean.
$PLSW(\text{-}2)$	-47.5938	23.6397	-2.0133	*
$PLSW(\text{-}3)$	34.7920	22.4488	1.5498	*
$PLSW(\text{-}4)$	-79.3338	20.3661	-3.7481	***
UVC	-1.2900	0.7712	-1.6725	*
C	177.0135	35.2989	5.0147	***
$R^2 = 0.8030$ $AIC = 5.4569$ $SC = 6.1882$ $HQ = 5.6597$				

*** significance at the level of 0.01, ** significance at the level of 0.05, * significance at the level of 0.1

Table 5. Test of F-between (based on `https://ec.europa.eu/eurostat` data).

Test Statistics	Meaning	p-value	$I(0)$	$1(1)$
			Asymptote: n=1000	
F-statistics	7.696768	10%	2.72	3.77
K	3	5%	3.23	4.35
		2.5%	3.69	4.89
		1%	4.29	5.61
Actual sample size	25		Final Sampling: n=30	
		10%	3.008	4.15
		5%	3.71	5.018
		1%	5.333	7.063

and is highly significant, indicating convergence. Therefore, it can be argued that 246.6% of the short-term to long-term adjustment occurs in less than four months.

7. Evaluation of model reliability

Subsequently, the assumptions about the stability of the model were checked and the characteristics of the residues were diagnosed. In particular, the cumulative residue test (CUSUM-test) by Brown, Durbin and Evans [47] showed that the evaluated model satisfies the stability condition, since there is no root lying beyond the significance level (figure 3).

The absence of consistent correlation of residues was verified using the LM test, and the hypothesis of the absence of heteroscedasticity was rejected at a significance level of 5% (table 7).

At the same time, the null hypothesis about the absence of a sequential correlation does not deviate at the level of 0.05, which indicates the absence of a sequential correlation in the

Table 6. Error correction model (based on `https://ec.europa.eu/eurostat` data).

Variable	Factor	Standard error	T-test	p-value
C	177.0135	27.9473	6.3345	***
$D(YLD(\text{-}1))$	0.8811	0.2878	3.0620	***
$D(YLD(\text{-}2))$	0.4750	0.1598	2.9714	**
$D(PLDW)$	15.0995	6.3900	2.3630	**
$D(PLDW(\text{-}1))$	-40.8889	6.9445	-5.8879	***
$D(PLDW(\text{-}2))$	-10.8965	7.0098	-1.5545	**
$D(PLDW(\text{-}3))$	-29.4581	6.5761	-4.4795	***
$D(PLSW)$	14.8428	13.4711	1.1041	*
$D(PLSW(\text{-}1))$	89.1355	15.2012	5.8637	***
$D(PLSW(\text{-}2))$	41.5118	174.6446	2.3543	**
$D(PLSW(\text{-}3))$	76.3338	14.9644	5.1010	***
ECT	-2.4662	0.3898	-6.3564	***
$R^2 = 0.9219$ AIC = 5.2169 SC = 5.8019 HQ = 5.3792				

*** significance at the level of 0.01, ** significance at the level of 0.05, * significance at the level of 0.1

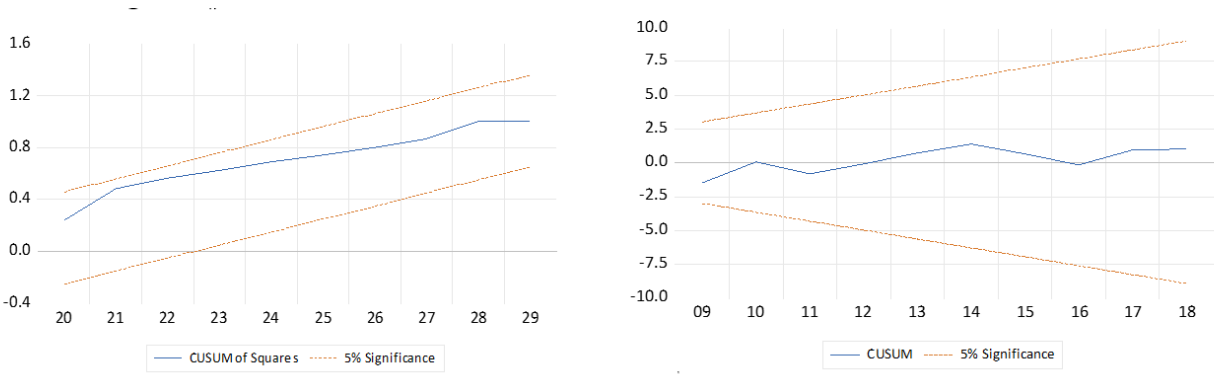

Figure 3. CUSUM and CUSUMSQ ARDL model stability tests (3,4,4,0) (based on `https://ec.europa.eu/eurostat` data).

Table 7. Sequential tests for the presence of residue autocorrelation and heteroscedasticity (based on `https://ec.europa.eu/eurostat` data).

Test	Meaning χ^2	p-value
Lagrange multiplier (LM) for sequential correlation	2.799107	0.1198
Breusch Pagan Godfrey test for heteroscedasticity	0.562511	0.8423

residuals of the model. In addition, there is no heteroscedasticity in the residues (that is, the variance is constant), as indicated by the Breusch Pagan Godfrey test.

To check the normality of the residues, the Jarque-Bera test (JB) was used (figure 4). His null hypothesis is that the residues are normally distributed. Given the graphical interpretation and the p-value, the probability at the level of 66.2% should be stated that the residuals are normal, so the null hypothesis is proven.

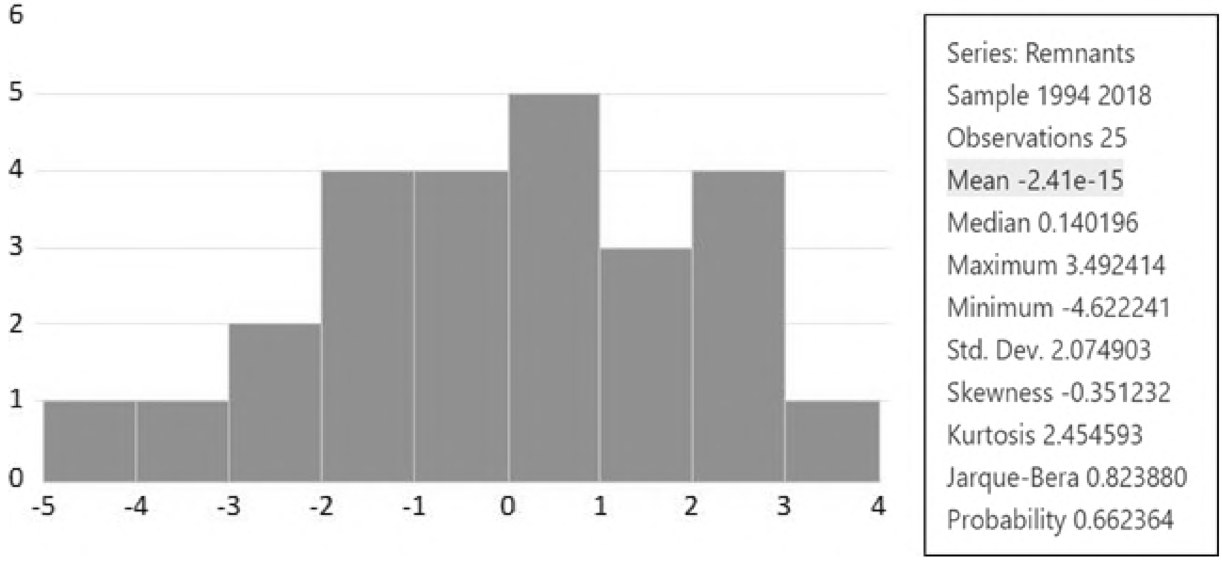

Figure 4. Normality diagram and Jarque-Bera test (based on `https://ec.europa.eu/eurostat` data).

8. Conclusions

1. Construction of the production function for the agricultural sector, in particular the grain sector, determines the consideration of internal and external factors of the organization of production and the conditions of its conduct. Unfortunately, this process involves a number of obstacles. Thus, taking into account the impact of land fertility on the basis of the bonitet score or economic valuation determines its correlation with other operating costs of the current and previous years, which distorts the results of modeling. Another difficult point is the non-synchronicity of the dynamics of grain prices and production resources, which necessitates bringing the indicators of costs and output to a comparable form, which determines the artificiality of comparison and non-stationarity of the dynamic series included in the model. One option to overcome these obstacles is to use a dependent lag autoregressive model (ARDL).
2. The variables of the wheat yield model were the indicator of operating costs at constant prices in 2010 and the payback of costs for the production of wheat grain for 1990-2018, as well as the lag values of the yield in the years preceding the reporting year, which made it possible to take into account the efficiency of using the production potential of the grain industry. Structural gaps in the dynamics of prices for purchased resources and wheat grain in the domestic Ukrainian market in 1990-2018, which led to its non-stationarity and prompted the construction of a model based on the indicators of farms in France for the same period. This made it possible to assess the conditions for the formation of costs and revenues of grain producers in the EU countries, on the eve of the accession of Ukraine and its grain industry to it.
3. The formed ARDL model is characterized by a high level of reliability, as evidenced by tests for the absence of sequential correlation and the absence of heteroscedasticity, as well as the Jarque-Bera test for the normality of the distribution of residues. The error correction model showed that the value of the ECT coefficient is negative, and the adjustment from short-term to long-term occurs in less than four months.
4. Modeling showed the non-equivalence of the influence of individual factors on the dynamics of yield. In particular, the p-value at the level of one percent has the payback of costs for

the production of soft wheat grain varieties of the reporting year, its first and third lag, as well as the second and third lag of recoupment of costs for the production of durum wheat. At the same time, there is an alternation of the sign of regressors, due to a decrease in prices in the years of excess grain production and their increase in lean years. The value of the unit cost regressor is also negative, while their lags according to the AIC criterion were not included. The prerequisite for this is the industrial nature of the technologies used. Thus, with an average yield of about 70 c/ha, the variation of the latter over the 29 years of the study did not exceed 7%, and therefore the increase in unit costs, and, accordingly, the yield, but does not provide a simultaneous increase in income due to a decrease in prices. In view of this, a negative value is logical cost regressor. Under such conditions, further study of the prerequisites should be aimed at studying the behavior of lag values of costs and the impact on their formation of a common European policy of regulating the productivity of agricultural production.

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Experimental research of time for opening and closing of spray in flat and injector nozzles

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Experimental research of time for opening and closing of spray in flat and injector nozzles

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Abstract. Experimental studies have been carried out to determine time for opening and closing of spray in Lechler ST 110-02 and IDK 120-02 nozzels for the combined spraying working body (CWB). The spray nozzles have been filmed by digital video camera. We received the results of opening time for nozzles and calculated the arithmetic mean, average square deviation (standard), and coefficient of variation by average square deviation. The opening time(arithmetic mean) for Lechler ST 110-02 flat nozzle 0,235 s. The opening time for Lechler IDK 120-02 injection sprays nozzle 0,435 s. The average value of the closing for spray in Lechler ST 110-02 is 0.04 s, and the Lechler IDK 120-02 nozzle is 0.08 s. The transient time for switching from the ST 110-02 nozzle to the IDK 120-02 nozzle should be 0.395 s, and the switching from the IDK 120-02 nozzle to the ST 110-02 nozzle should be 0.155 s.

1. Introduction

The intensification of agricultural production and the widespread introduction of mechanized technologies for growing field crops require the rational use of chemical plant protection products. A significant variety of soil and climatic conditions, meteorological factors, contamination of fields with many types of weeds, a large set of cultivated plants and many other factors necessitate the introduction of modern plant protection machines, especially the ability to adjust such important parameters as working fluid consumption and dispersion during the work process.

Many scientists have been studied technological processes and working bodies for chemical plant protection:

- flow and pressure regulation for agricultural sprayers using solenoid valves [1];
- comprehensive model of pesticide spray drift with an assessment in vineyards [2];
- flow, spray pattern, and droplet spectra characteristics of an electronically actuated variable-orifice nozzle [3];
- effect of nozzle type and pressure on spray droplet characteristics [4];
- machine protection equipment, describing its characteristics, process flow charts, settings, and methods of use [5];
- improvement of dispersion for pesticide spraying [6];
- substantiation of parameters of the pneumohydraulic system for dosing and supply of working fluid in sprayers [7];
- jet pump for direct supply of pesticides to the sprayer discharge communication [8].

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The analysis of the well-known authors works have been showed that we don't have the research of time for opening and closing of spray in flat and injector studies have been carried out to determine time for opening and closing of spray in flat and injector nozzles of the combined spraying working body (CWB).

2. Materials and methods

The research was being conducted at the National University of Life and Environmental Sciences of Ukraine at the Department of Agricultural Machinery and System Engineering named after Academician P. M. Vasylenko in 2021-2023.

The main factor that affects on the speed of the droplet departure from the spray nozzle, and therefore the time for opening and closing of spray in flat and injector nozzles, it is the pressure in the spray manifold.

Since it is impossible to record the time of opening and closing of the spraying plume using a stopwatch and visual organs, we decided to film it using a Panasonic NV-GS75 digital video camera, which allows you to take 25 frames per second.

The experimental sprayer OP 2000-2 has being transported to the test site. A cardan shaft have been attached to the sprayer pump and connected to the PTO of the MTZ-82 tractor. The tractor PTO speed was 540 rpm.

The pressure in the manifold was being monitored using a WIKAI EN837-1 manometer [9]. Since the sprayers operate at a pressure 0.2 to 0.5 MPa, the tests have been conducted at the average pressure 0.35 MPa.

The Panasonic NV-GS75 digital video camera have been mounted on a Continent TRIPOD A2 tripod. The installation height of the video camera was 1 meter above the ground and 1.5 meters to the CWB. The video camera was set to a shutter speed of 1/500 second, an aperture of $D = 8$ to ensure the highest clarity, and a 10x optical zoom. The shooting has been carried out in triplicate, on three sections of the boom, each type of sprayer have been filmed separately (figure 1).

After the research, the camera has been connected using a FireWire connector to the PC based on an Athlon 2800+ processor. The video has been processed using the Motion DV STUDIO 5.3E program, where the time for opening and closing of spray in flat and injector nozzles for the CWB has been calculated (figure 2).

The research data has been processed according to the method of statistical processing for empirical data and have been evaluated by the arithmetic mean time of opening and closing for the spray nozzle of the combined spraying working body.

The arithmetic mean value the time of opening and closing for the spray nozzle has been determined by the following equation [10]:

$$X = \frac{\sum x_i}{N}, \tag{1}$$

where the X – time for opening or closing of spray nozzles, second; N – the number of experiments.

The dispersion had been calculated by the following equation [10]:

$$\sigma^2 = \frac{\sum (x_i - X)^2}{N - 1} \tag{2}$$

The average square deviation (standard) had been calculated by the following equation [10]:

$$\sigma = \sqrt{\sigma^2} \tag{3}$$

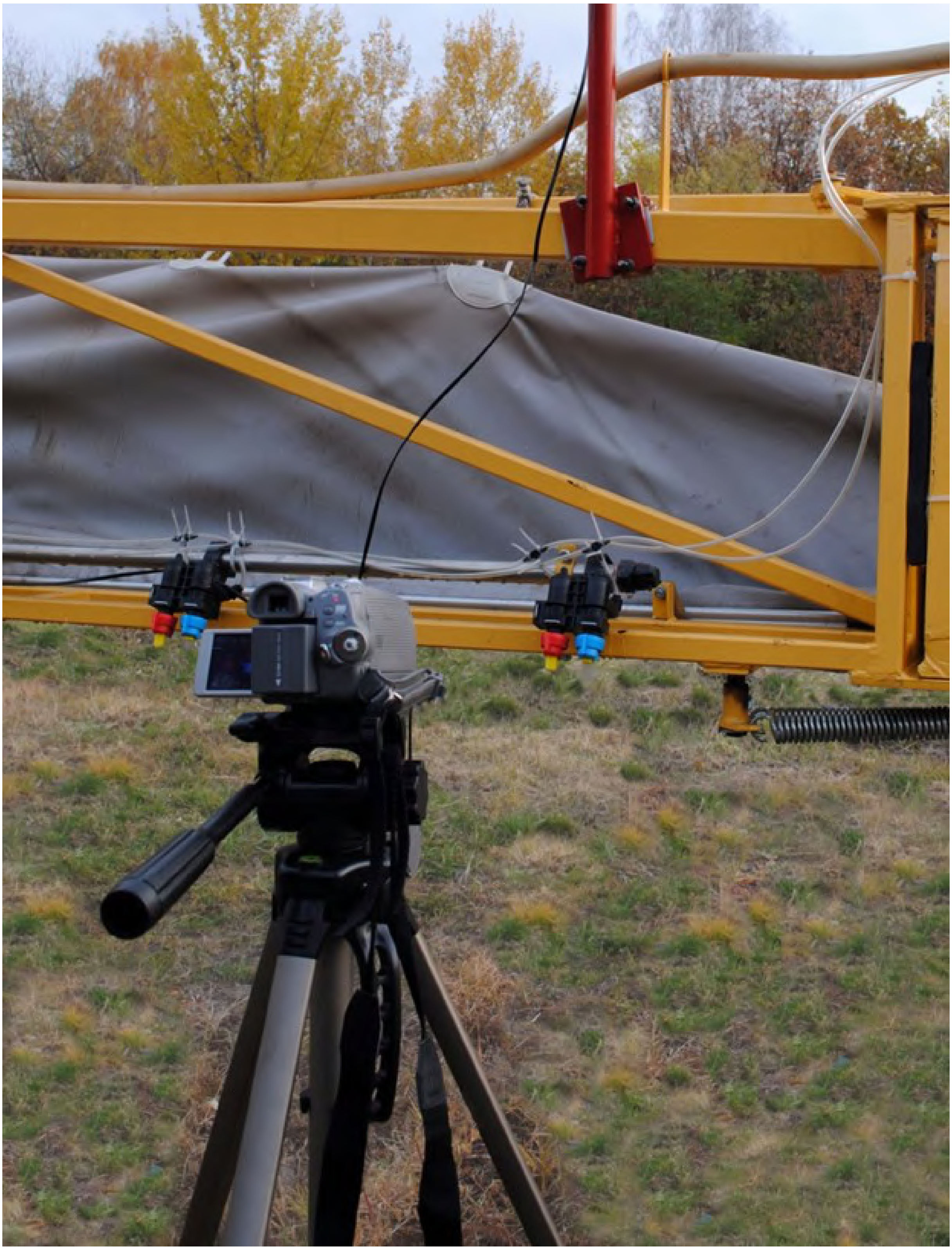

Figure 1. Filming of opening and closing of spray in flat and injector nozzles.

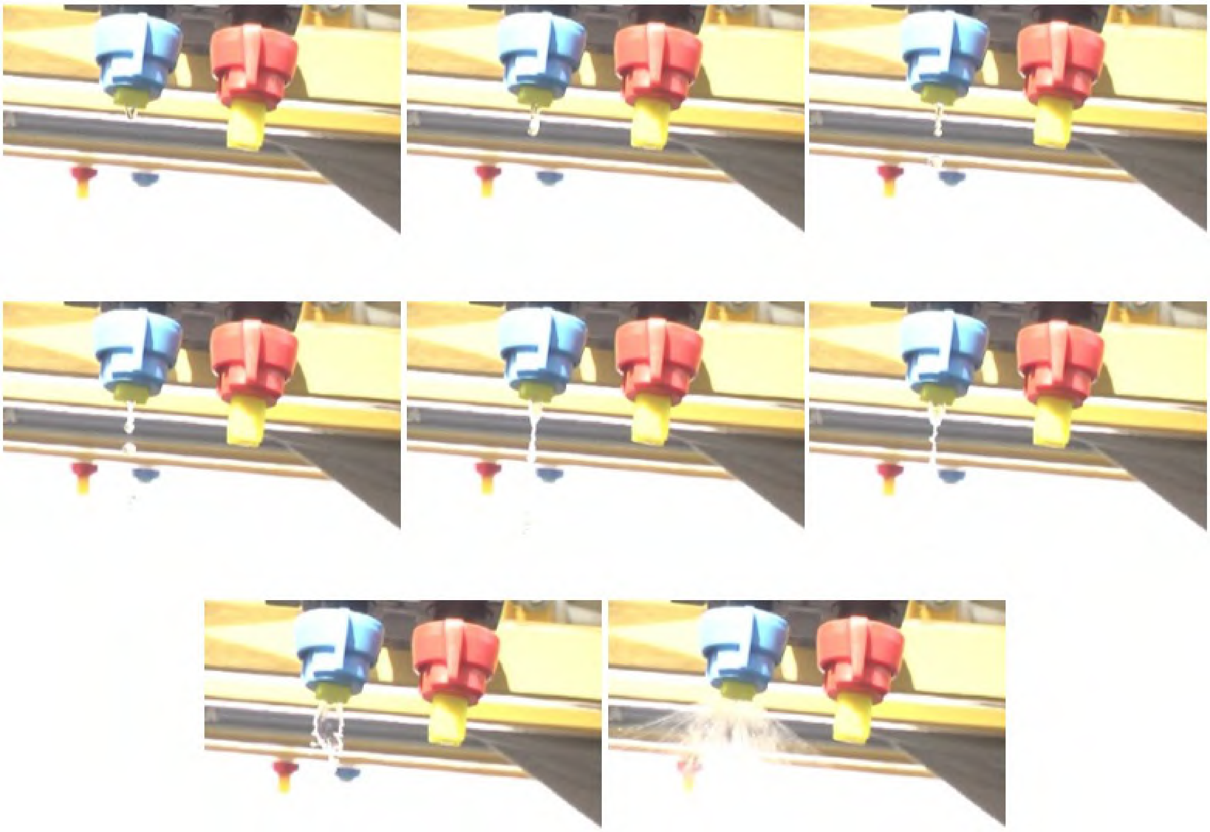

Figure 2. Opening of the Lechler ST 110-02 spray nozzle (photo interval – 0.04 s).

The coefficient of variation by average square deviation had been calculated by the following equation [10]:

$$V = \frac{\sigma}{X} * 100\%. \quad (4)$$

3. Results and discussion

The results of the data (arithmetic means from three sections, three repetitions) you can see in figure 3 and figure 4.

The arithmetic mean has been determined with help of equation (1). Calculations have been performed using Microsoft Office Excel software.

The results of calculations for arithmetic mean, average square deviation (standard), and

Table 1. Results of calculations for experimental studies.

Opening time, seconds	Arithmetic mean	Dispersion	Average square deviation (standard)	Coefficient of variation
Lechler ST 110-02 flat nozzle	0.235	0.002	0.045	19.17
Lechler IDK 120-02 injection spray nozzle	0.435	0.005	0.068	15.55

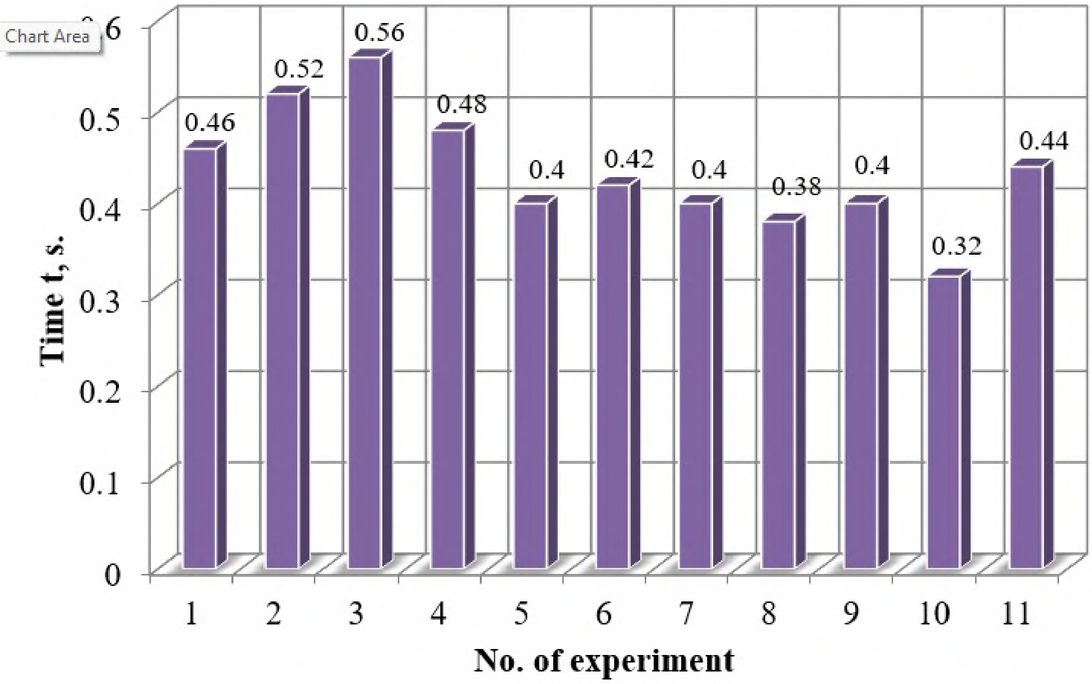

Figure 3. The opening time for Lechler IDK 120-02 injection spray nozzle.

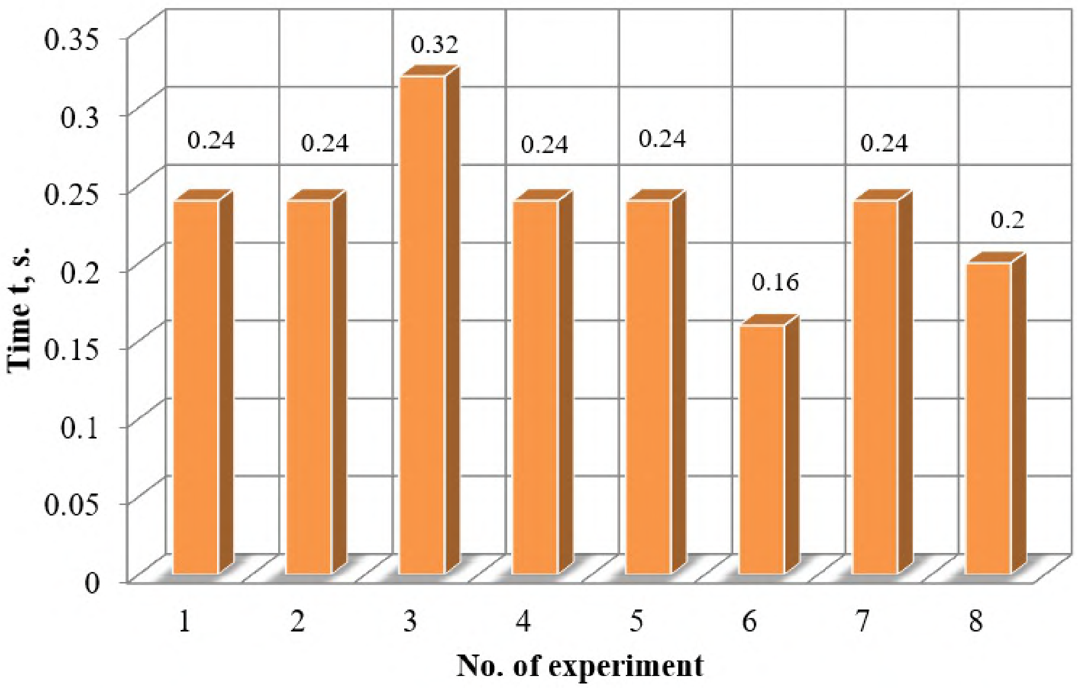

Figure 4. The opening time for Lechler ST 110-02 flat nozzle.

coefficient of variation by average square deviation you can see in table 1 (calculations have been performed using equations (1)-(4)).

The average value of the closing of spray in Lechler ST 110-02 is 0.04 s, and the Lechler IDK 120-02 nozzle is 0.08 s.

4. Conclusions

The opening time(arithmetic mean) for Lechler ST 110-02 flat nozzle 0.235 s. The opening time for Lechler IDK 120-02 injection spray nozzle 0.435 s. The average value of the closing for spray in Lechler ST 110-02 is 0.04 s, and the Lechler IDK 120-02 nozzle is 0.08 s. The transient time for switching from the ST 110-02 nozzle to the IDK 120-02 nozzle should be 0.395 s, and the switching from the IDK 120-02 nozzle to the ST 110-02 nozzle should be 0.155 s.

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Exploring sustainable choices: Consumer perception factors of millet milk consumption

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Exploring sustainable choices: Consumer perception factors of millet milk consumption

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Abstract. Plant-based dairy alternatives have been gaining popularity recently in developing nations, but only a little is known about the consumer perception of these goods. This study aims to analyze the key determinants that affect millet milk consumption in India. An online survey was conducted with a sample of 178 people belonging to different age groups and educational backgrounds. Binary logistic regression was used in the study to analyze the factors that will significantly contribute to the consumption of millet milk. The results suggested that veganism and ethical concerns significantly affected decision-making. In addition, the educational background of the people was also significant but negatively correlated in influencing the consumption of plant-based dairy alternatives. The study aligns with SDG 12: Sustainable Consumption and Production, SDG 13: Climate Action, and SDG 3: Good Health and Well-being, contributing valuable insights for fostering sustainable dietary patterns and environmentally conscious consumer behavior. To promote millet milk in the Indian market, the stakeholders can customize their marketing strategies and emphasize ethical concerns and veganism.

1. Introduction

Milk and milk products are an integral part of the Indian diet and are one of the most accepted sources of nutrition. They are usually sourced from cows, goats, and buffalos and serve as regular human food. Nevertheless, the number of people experiencing lactose intolerance has extensively ramped up. This rise in the lactose-intolerant population focuses on the need and scope for seeking alternatives to dairy milk [1]. The non-dairy milk alternatives are sourced from plant sources such as cereals, legumes, nuts, seeds, pseudo-cereals, and so on [2]. This plant-based milk is a juice derived from plant extracts and water, resembling the colour of bovine milk, but has a different taste.

Plant-based alternatives have higher calcium, potassium, and vitamin content and lower amounts of fat, sugar, and saturated fat content when compared with regular bovine milk. Cereal-based milk is now majorly developed from oats, rice, etc.; millet is a new addition to this category. Being high in protein and low in calories, it is an ideal replacement for dairy, especially in the current scenario where high nutrition and low calorie is preferred. The high fiber content of millet makes digestion slow, prolonging the body's energy supply [3]. Although they are superior to other cereals, their utilization as food, especially as a milk alternative, is minimal. Millets are extensively cultivated in India and they are known to thrive well in all soil types with less maintenance and less water, making them a sustainable crop that has the potential to meet the food security needs of our country [4]. Therefore, it is an ideal crop to be used as a dairy replacement through value addition. The immense potentialities that millet milk and its dehydrated products possess could also be utilized in developing novel food products at the therapeutic end [5]. Therefore, this study aims to analyze the millet milk market in India.

In this context, the study is involved in identifying what are the crucial factors involved in the purchase of millet milk. The primary motivation for conducting this study is the growing popularity of plant-based diets and the trend towards veganism and sustainability. This study aims to investigate the aspects that influence the uptake of millet milk, such as its nutritional value, personal taste preferences, environmental concerns, animal welfare ethics, age demographics, and the influence of education on people's dietary decisions. The study aims to offer insights into the developing market dynamics of plant-based dairy substitutes, especially millet milk, in response to shifting consumer habits and health-conscious trends by examining these variables. The study directly tackles the objective of encouraging sustainable consumption (SDG-12), good health and well-being (SDG-3), and climate action (SDG-13) by analyzing the determinants of millet milk consumption in the context of plant-based dairy substitutes. The research's conclusions can help promote environmentally friendly purchasing behaviour and sustainable eating habits.

2. Literature review

Over the past few years, the idea of veganism, which originated predominantly in the Western world, has gracefully found its way into Southeast Asian homes. Alongside the well-known soy and almond milk choices, other alternatives, such as oats, cashews, peas, and hemp milk, have also placed their foot in the Indian markets. Millet milk is a new addition to this family.

Plant-based milk presents an acquired taste distinct from the familiar fresh cow's milk that Indians have traditionally grown up with, and this is a newer concept in India [6, 7].

Millet is the sixth most important cereal in the world and is considered a rich source of energy, protein, and minerals [7]. Unprocessed millet milk contains 9.17 percent protein, three times more than dairy milk, and 0.68 percent fat, 1.7 times less than dairy milk [8]. They also contain significant aggregates of carbohydrates (60-70 percent), dietary fibers (2-7 percent), and minerals, especially calcium, iron, zinc, and iodine [9]. In addition to this, some components present in millet, such as phytates, phenol, and tannins, provide anti-aging benefits. The high amount of bioactive and antioxidant compounds and low levels of saturated fats in millet help maintain positive health by preventing the onset of non-communicable diseases like obesity, cardiovascular disease [10], inflammatory disease, and diabetes mellitus [11]. Dietary fiber and micronutrients in millet help maintain health and prevent type-2 diabetes, breast cancer, and heart diseases [12]. They match nearly all the most prominent global health food trends, including being a superfood, ancient grain, gluten-free, low glycemic index, high in antioxidants, and suitable for managing weight [13]. When considering these factors, and due to numerous other water-soluble nutrients, millets are a good source for developing plant-based milk substitutes.

There has been a significant increase in consumer interest in natural and healthy foods, especially since the COVID-19 pandemic. The rise in millet consumption can be ascribed to increased health awareness. People are turning to a millet-based diet to improve and rant up their immunity levels and to have a healthy lifestyle, recognizing food as a medicine [14]. In India, many entrepreneurs and food companies have shown interest in using millet lately after understanding its nutritional benefits in various modern products, including flour in pancakes, pasta, and noodles. Popped, flaked, and puffed millet variants are used in snack bars and as breakfast cereals [15, 16].

An investigation into the connection between the attributes of dairy-alternative drinks and consumers' propensity to buy shows that nutrient-related health characteristics, such as calories, protein, fat, and vitamins, matter to them [17]. Besides nutritional benefits, the product's taste was another crucial factor influencing plant-based beverage purchases. Taste preference plays a significant role in buying milk, leading to the hypothesis that it is inversely related to purchasing plant-based milk [18]. This assumption is based on the understanding that individuals who prioritize taste in their choice of milk might be less inclined to opt for plant-based alternatives. Millet milk has attracted the attention of lactose-intolerant and vegan consumers today. According to Good Food Institute India (GFII), the market for these plant-based dairies is still driven by lactose intolerance, ramped-up demand for vegan food options, and climate change. The increase in dietary restrictions and growing adoption of veganism, a dietary style of consumers, is predicted to positively influence the consumption of plant-based milk dairy [19,20]. This assumption is based on the knowledge that people who follow particular dietary guidelines and preferences, such as veganism or lactose intolerance, are likely to influence the growing acceptance of plant-based milk substitutes like millet milk.

Environmental concerns might be another factor driving individuals to choose plant-based dairy substitutes in addition to their benefits to health, affordability, and flavor [19]. Furthermore, people who view animal welfare as a critical consideration when choosing foods view plant-based dairy alternatives as more ethical [20]. Therefore, environmental and ethical concerns about animals positively influence consumers' perception of plant-based dairy alternatives [19]. Along with plant-based dairy substitutes' objective nutritional qualities, what customers think about this product category also matters, which is why this study focuses on understanding the factors that lead to the purchase of millet milk.

Young individuals are more liberal in consuming plant-based milk [21]. Therefore, age is expected to have a negative influence. It is claimed that younger and middle-aged individuals are expected to be more curious and open to trying new items in the market than older individuals. This anticipation is anchored in the fact that younger and middle-aged groups frequently demonstrate greater openness to innovative experiences and innovations. Thus, it was expected to influence the choice of plant-based beverages positively. Education gives people the information and analytical abilities they need to choose healthier foods [22]. Therefore, it is expected to affect Individuals' nutritional choices positively. It is assumed that in this particular setting, people with greater levels of education are more likely to prioritize nutrition, which will positively impact their total dietary choices.

3. Methodology

3.1. Methods and procedures

The study is designed as a quantitative study to gain insights into the relatively unexplored phenomenon of millet milk consumption among consumers in India. While millet milk and its products offer numerous health, environmental, and ethical advantages compared to traditional bovine dairy, it is essential to understand the factors that drive consumers to purchase.

Data regarding the current market size and growth trends of plant-based non-dairy in India was collected through secondary sources such as existing studies, industry publications, research firms, and other reliable sources. This will help to understand the demand for existing plant-based, non-dairy beverages in India.

More participants will participate in a survey online rather than in a traditional one-to-one setting [23]. Hence, an online mode was adopted in this scenario. A structured survey was prepared in Questionpro for primary data collection. It was distributed to all potential participants from November to December 2023 to understand the consumer perception of millet milk across India. The questions were tailored explicitly to analyze and understand the fundamental driving forces and barriers in consumers' minds.

The survey was distributed through various online and social media channels to reach a broad audience across India. Efforts were made to target individuals from urban, suburban, and rural areas to ensure geographic diversity. This study has recorded 178 opinions from 6 questions to understand the market acceptance and challenges of millet milk in India. The survey predominantly concentrated on individuals aged 20 and above as they have higher chances of being employed and will have their own opinions on the food items they consume. Most respondents (about 90 percent) from the sample were over 20 years old and above. 50.54 percent of the respondents said that they had consumed plant-based milk earlier. Regarding gender, females comprised almost 53.51 percent of the sample, while males contributed the remaining 46.49 percent. Nearly 9.19 percent of the individuals surveyed only had senior secondary education as their educational qualification, and 32.97 percent had completed undergraduate degrees. While 46.49 percent of the individuals had post-graduate and 11.35 percent had doctorate qualifications. In total, 90.8 percent of individuals qualified for undergraduate and above degrees.

The transcriptions of the questionnaire were moved to Excel format and analyzed using the Statistical Package for Social Sciences (SPSS). At First, a cleaning process was performed to guarantee its completeness and validity. This procedure examined logical inconsistencies, outliers, and missing numbers. The values of the means and standard deviations of the variables were generated to prevent these data issues. Based on these values, no missing values were found, but some outliers were discovered. The outliers were handled by substituting them with the mean values of each variable.

This study utilized binary logistic regression to identify the significant factors that influenced the consumers' purchase decision of millet milk. A binary logistic regression is a kind of regression model where the dependent variable is a categorical dichotomy that can have just two values, one or zero [24].

3.2. Model specification and variable description

Since the likelihood of customers' replies was a binary decision, the binary logistic regression model was employed for the study. The dependent variable measured the consumers' choice regarding plant-based dairy alternatives (either consumed or never consumed). In contrast, independent variables were derived from the consumer's demographics, such as age, gender, educational background, and veganism. Characteristic variables influencing a consumer's purchase include dietary restrictions, curiosity to try a new item, taste preferences, ethical concerns, and environmental factors. These variables included in the study were consistent with the literature. The age of the individuals represents the age of the consumers in years, and the education of the individuals was measured in the years of schooling under two categories: graduation and above and below graduation. Finally, bivariate correlation analysis was conducted to test the correlation between the factors that led to the purchase of millet milk.

4. Results and analysis

4.1. Descriptive analysis

The dietary style of individuals was recorded as vegan or non-vegan. Among the transcripts, almost 87.91 percent of the individuals surveyed were identified as either vegetarians or omnivores, while only 12.09 percent were vegans. This breakdown is essential for comprehending the market segment that is either open to or interested in embracing plant-based milk substitutes like millet milk. Among the factors influencing individuals' milk purchases, the main motivator was tasting preference, followed by considerations for nutrition, the environment, and the ethical treatment of animals. It is essential to comprehend these impacting elements to address customer preferences and customize marketing methods properly.

Table 1. Variable definition, unit of measurement, and expected signs.

Variable code	Variable name	Measurement	Expected signs
Dependent variable			
cnsptn	Consumption of Millet Milk	1 if yes, 0 if otherwise	
Independent variables			
Age	Age of Individuals	Number of Years	−
Gen	Gender of the Individuals	1 if Male, 0 if Female	
Edu	Education of the Individuals	Years of Schooling	+
Vegan	Dietary Style of Individuals	1 if yes, 0 if otherwise	+
Curi	Curiosity to try new items	On a scale of 1-7	+
Nutri	Nutritional content of milk	On a scale of 1-7	+
Diet	Dietary Restrictions of Individuals	On a scale of 1-7	+
Envi	Environmental Concerns	On a scale of 1-7	+
Taste	Taste Preferences	On a scale of 1-7	−
Ethical	Ethical Considerations	On a scale of 1-7	+

4.2. Factors affecting millet milk consumption: Binary logistic regression analysis

This study used binary logistic regression analysis to determine the parameters impacting plant-based milk consumption in India. The estimated variables are shown in Table 2. The explanatory variables in the model's estimated coefficients (B), standard error (S.E.), significance value (sig.), and odds ratios were displayed in the table. If all other predictors are identical, the coefficients (B values) estimate the changing likelihood of the dependent variable for a unit change in the related predictor [25]. The sign of the coefficient values indicates the explanatory variable's direction of impact. The model was very significant (P-value of 0.000) in predicting consumers' millet milk choices.

The explanatory factors significantly influencing millet milk consumption were veganism, educational background, and ethical treatment. However, age, gender, nutritional factors, environmental concerns, taste preferences, nutritional content, curiosity, and dietary restrictions (like lactose intolerance) were not statistically significant. Also, the signs of the estimated coefficients of some independent variables aligned with the prior expectations; however, others were contrary to expectations.

The variable 'veganism' was found to influence the purchase of millet milk in India significantly. The beta coefficient of this variable was 1.614, with an associated P-value of 0.010. The effect of this dietary culture on the purchase turned out to be positive, as expected. Similarly, the ethical concerns about animals significantly influenced the purchase with a beta coefficient value of 0.333 and an associated P-value of 0.015. This variable had a positive influence. This explains that the more ethical concerns individuals have towards animals, the greater their chances to shift towards a plant-based dairy. This result was well aligned with the previous study, which concluded that people with an ethical concern towards animals are more likely to turn to millet milk [19].

The variable 'educational background,' although significant, demonstrated a negative effect on the consumption of millet milk. This finding did not support the previous results, which report that education will have a positive influence [22]. The reason for the above could stem from individuals being reluctant to break with their long-standing cultural custom of drinking cow milk. Despite being informed about the advantages of plant-based milk, people may exhibit reluctance to embrace dietary choices that align with their well-established traditions. One possible explanation for this resistance to switching to healthier options is a reluctance to deviate from cultural norms and practices [26]. As stated, though people know the nutritional benefits, none of this intellectual knowledge is reflected in their eating habits. Similarly, even nutritional content did not significantly influence the purchase. This could be because consumers prioritize taste and texture above nutrition. These results align with the previous study, which states that consumers of cow milk need to have 1-2 percent fat content in their milk and perceive it as a staple food [27].

Table 2. Binary logistic regression results in identifying the factors influencing the consumption of millet milk in India.

Variable	B	S.E	Sig.	Exp (B)
Age	0.008	0.17	0.645	1.008
Gen	0.199	0.340	0.558	1.220
Edu	-1.260	0.739	0.088	0.284
Vegan	1.614	0.626	0.10	5.024
Curi	0.028	0.130	0.831	1.028
Nutri	-0.38	0.149	0.798	0.963
Diet	-0.067	0.122	0.582	0.935
Envi	0.225	0.168	0.179	1.253
Taste	0.214	0.154	0.165	1.238
Ethical	0.333	0.137	0.015	1.395
Number of observations	178			
Log likelihood	210.885			
Chi-Square	34.484			
Sig. chi-square	0.000			
Nagelkerke R2	0.236			
% Correct predictions	65.5			
a B = coefficients				
b SE = standard error				
c Sig. = significance value				
d Exp (B) = odds ratio				

Other factors, such as environmental concerns, curiosity to try a new item, and taste preferences, had a non-significant effect on the purchase of millet milk. This result did not support previous studies, which concluded that the above factors would positively influence the purchase of millet milk [19, 28]. Remarkably, those concerned about the environment only sometimes chose plant-based dairy substitutes over conventional cow's milk. This confirms that individuals only sometimes express ecologically conscious consumer behaviour [28]. The study also found no statistically significant influence of milk's taste on customers' selection of millet milk. This supports the findings that full-fat dairy milk was preferred over plant-based dairy alternatives [29]. These results imply that although various factors influence consumer decisions, tastes, curiosity, and environmental concerns do not significantly impact the preference for millet milk over traditional options. Overall, the binary logistic regression has yielded insights into the critical factors that affected millet milk intake in India. Of all their demographic characteristics, only the veganism of the customers' diet was the most significant factor influencing their buying choice. Animal ethics also has a significant role to play in the purchasing process.

5. Conclusion and recommendations

The study reveals several key insights with implications for companies and stakeholders promoting millet milk in India. Veganism has been found to influence the consumption of millet milk significantly, indicating that those who follow a vegan diet are more likely to choose plant-based alternatives. Consistent with earlier studies, the study indicated a favourable association between the decision to use millet milk and ethical concerns regarding animals. People who cared deeply about animal welfare as an ethical issue were more likely to select plant-based dairy alternatives.

Surprisingly, individuals with greater educational backgrounds negatively influenced millet milk intake, even though their effect was statistically significant. This might be explained by cultural inertia, a phenomenon in which dietary changes are resisted despite knowledge of the advantages of plant-based alternatives due to ingrained customs and behaviours. These findings showcase the context-dependent nature of consumer behaviour in the adoption of millet milk. The non-significant influence of environmental concerns, curiosity, taste preference, nutritional content, age, gender, and dietary restrictions underscores the need for a more comprehensive understanding of the diverse elements in shaping consumer preferences for plant-based milk alternatives.

Given that veganism has a major impact on the consumption of millet milk, businesses should focus their marketing efforts on this expanding vegan market. To attract this customer niche, it may be useful to highlight the plant-based character of millet milk and its compliance with ethical and animal welfare issues.

Conversely, the negative effect of educational background on millet milk intake suggests that awareness initiatives focusing on the health advantages of millet milk need to be revised. Companies need to acknowledge the cultural and traditional aspects of dairy consumption, including the standing tradition of consuming cow's milk. Strategies must be devised to address and potentially overcome these cultural barriers, emphasizing the health benefits without directly challenging cultural norms. Despite the non-significant influence of nutritional content, there is room for educating consumers on the health benefits of millet milk. Providing consumers with clear information about the benefits can help bridge the gap between consumption and awareness.

Overall, the study emphasizes the importance of understanding the factors affecting the intake of millet milk. This study adds unique insights into the dynamics of sustainable choices in the food sector (SDG-12), climate action (SDG-13), and good health and well-being (SDG-3), shedding light on the intricate interaction of ethical concerns, dietary preferences, and educational variables in determining the consumption patterns of millet milk in the Indian market. To effectively promote millet milk in the Indian market, companies and stakeholders should customize their promotional activities to emphasize ethical issues, target specific customer categories like vegetarians, and overcome cultural hurdles. Furthermore, realizing that environmental concerns and taste preferences are not the main motivators helps improve marketing techniques. More research is advised to explore these areas in greater detail. The omission of price as a factor in our study was due to the early stage of the millet milk market in India, where awareness about pricing dynamics is currently limited among consumers. The study acknowledges the significance of price in shaping consumer behavior and consumption patterns. Incorporating price or the relationship between household income and the affordability of millet milk in future studies will enrich the understanding of the dynamics surrounding millet milk consumption. Additionally, future studies can include factors influenced by varying socio-economic contexts by examining consumption preferences across different demographic segments, including rural and urban populations. Knowing the subtle aspects influencing consumer decisions can help the millet milk industry improve its marketing tactics and product development initiatives.

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Assessment of changes in the structure of the forest ecosystems for example sanitary woody plantations in the Steppe Dnipro

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Assessment of changes in the structure of the forest ecosystems for example sanitary woody plantations in the Steppe Dnipro

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Abstract. The main acceleration of climatic changes is considered to be the main consequences of existing anthropogenic influences and transformations in the wood ecosystems of the Steppe Dnipro industrial areas. Now, the preparation of science-based programs for the restoration and development of artificial tree plantations, which can increase the stability and diversity of forest ecosystems in the steppe zone under these conditions, is very important. However, artificial tree and shrub plantations are formed according to certain natural laws. It is necessary and urgent to study the current state of phytodiversity to ensure the effective protection of biodiversity, and implement nature conservation management on this basis, including the expansion of the areas of nature reserves. The purpose of this research work was to assess changes in the structure of the Dnipro Steppe woody ecosystems using the example of dust-protection and water-protection sanitary plantations. Modern biodiversity, formed in the natural ecotopes of the Steppe Dnipro region of Ukraine, is quite specific, primarily due to the combination of natural and anthropogenic landscapes in these territories. Depending on the ecological location territory conditions, taking into account the vitality indicators of the plantations, the further development of woody ecosystems according to the vectors of progress or regression is possible. Hence, there is an urgent need to study the biometric indicators of the Kryvyi Rih district's woody ecosystems under different growth conditions. The work carried out will become the basis for the development of the main directions of preservation and reproduction of phytodiversity in the woody ecosystems of the territory, which will make it possible to plan the necessary vectors for the protection and restoration of biological diversity of artificial trees and shrub plantations of the Kryvyi Rih districts. identifying the features of local guarantee of rare species from various protection lists. It will also contribute to the provision of ecosystem services by natural, spontaneous and artificial woody plantations of the Middle Dnipro region. The received recommendations form the basis of complex measures to preserve and restore the stable state of artificial tree plantations of the Kryvyi Rih district, located on the steep slopes of mine dumps and rafter-beam systems near the rivers and water reservoirs of the Dnipro Steppe.

1. Introduction

Acceleration of industrial and technical greenhouse gas emissions and disruption of the energy balance of the atmosphere, which is characteristic of powerful industrial regions in Ukraine, are considered the main causes of the existing climate changes [1–4]. Now the emergence and manifestation of catastrophic degradation phenomena, such as the development of the desertification process in the southern and Ukraine southeastern regions, are also associated with military operations and pyrokinetic effects and chemical pollution in the cycle of nutrients in the Dnipro Steppe natural and artificial woody ecosystems. The analysis of the main multi-year ecological consequences of global climate violation such as warming, as well as changes in the conditions of growth and development of tree ecosystems determines the further direction of work on acclimatization and introduction of woody plant species. Identification of new woody introduced taxons, the invasion of which has already occurred or may occur in the near future in Ukraine is an important area of ecological and botanical research. When studying the impact of climate change on woody and shrub plants used in landscaping and agriculture, it is also necessary to take into account the characteristics of nutrition with soil microelements and moistening with underground and above-ground water resources [5–12].

In the Ukrainian steppe territory the spatio-temporal transformation of the woody ecosystems structure is associated with changes in the water ecosystems of the Azov Sea and the Kakhov reservoir, the destruction of which in 2023 led to an ecological disaster of a regional scale. At the local level, the state of tree ecosystems will depend on the river ecosystems of the Dnipro region, such as Saksagan, Ingulets, Kamianka, Bazavluk, Samara, etc.

Under these conditions, scientifically based restoration and preservation of woody ecosystems in the conditions of the steppe zone is important. However, artificial woody and shrub plantations form according to certain natural orders [1, 2, 6, 13–16]. Depending on the ecological conditions of theterritory location and the complex of viability indicators of woody ecosystems, their further development is possible according to the vectors of progress or regression. Hence, there is an urgent need to study the biometric indicators of woody ecosystems in Kryvyi Rih district under different growth conditions.

Sustainable forest management (SFM) is currently widely recognized as the main goal of forest policy and practice in leading European countries [17–19]. RRegional processes for the development and implementation of SFM criteria and indicators are ongoing worldwide. In continental Europe, a set of 35 pan-European indicators has been endorsed by the Ministerial Conference for the Protection of Forests in Europe (MCPFE) to measure progress towards SFM in 44 countries in the region [18, 20, 21]. The importance of studying various aspects of modern phytodiversity as an essential element of preserving woody ecosystems for the development of a national ecological network in the pan-European network system is also an applied direction for the natural environment restoration as a result of ecocide caused by military actions in Ukraine. For this purpose, it is necessary to investigate various characteristics of natural and spontaneously formed woody plant cover. Given the ecological specificity of the Middle Dnipro and the Forest-Steppe zone in Ukraine, a detailed analysis of natural and artificially formed woody plantations on man-made landscape formations, in raft-beam systems of rivers and reservoirs, as well as in floodplain woody ecosystems is required.

A lot of studies (e.g., [11, 17, 19–22]) discusses European approaches to the concept and requirements for a classification of woody ecosystem vitality that is more ecologically substantiated and suitable for MCPFE revealing. In Europe a unified approach to the of tree ecosystems classification implemented as part of the MCPFE monitoring process and its analysis, is reported to be resulted in a proposed European forest types scheme structured into a reasonably large number of classes, which improves the specificity of indicators.

In the experts works on the protection and preservation of Ukrainian woody ecosystems, the features of forest ecosystems, the distribution of tree species and the ecological conditions of their

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growth are given. According to forest management data, the area covered by forest vegetation is 251341.3 hectares [23,24]. On the Middle Dnipro region territory the distribution of the forest plots area on edatopes, natural and artificially formed forests on the Dnipro steeps, in rafter-beam systems and in the floodplain of the Dnipro River and the Forest Steppe of Ukraine is as follows: trophotopes – subory (78083.2 ha, 31.07 %), conifers (77232.6 ha, 30.73 %), thickets (72520.6 ha, 28.85 %) and boreal forests (23504.9 ha, 9.35 %). hygrotopes – fresh conditions (183792.4 ha, 73.13 %), dry (34938.5 ha, 13.90 %), wet (19038.7 ha, 7.57 %), crude (11401.1 ha, 4.54 %), moist (1896.0 ha, 0.75 %) and very dry conditions (274.6 ha, 0.11 %) [23–25].

Up day, the tendency to intensive use of forest resources caused by the desire of forest industry enterprises to obtain high profits dictated by the market increases in the Kryvyi Rih district. On the other hand, currently the forestry land area amounts to 9,086 hectares, of which 6,500 hectares are forest land. On the main part of these lands, only the natural regeneration of the forest is taking place, while an recent years afforestation has been carried out on area of only 2 hectares.

The change in the vital state of woody ecosystems depends on several environmental factors – abiotic, biotic and anthropogenic. However, it is always possible to single out complex of key factors that have the greatest impact on tree regeneration, drying and waste, invasive introduction of aggressive tree species, etc. Factors regulating the population density of woody ecosystems are divided into density-dependent and density-independent factors. Homeostasis of the tree ecosystems population is defined as the ability to maintain a certain number (density) and self-regeneration of the dominant species of tree vegetation in Kryvyi Rih district. A significant period of forest resources reproduction limits the possibilities of their use, especially in the unfavourable conditions of the steppe climate and constant anthropogenic load. Such specificity of woody plantations requires constant monitoring of relevant changes in the species composition and vital state at the tree in ecosystems. This demands the improvement of the forest management system, the creation of environmental protection infrastructure governance, and the development of a financial and economic system of targeted financing of the forest protection industry [3, 6, 18, 22, 26, 27].

The work aim is evaluating the changes in the structure of forest ecosystems using the example of dust-protection and water-protection sanitary woody plantations, analyze the vital state of artificial woody plantations and the stability of the dominant tree layers representatives, caused by the stress factors of anthropogenic load industrial-residential nature and the region arid climate for further improvement of the forest resource management system and governance of nature protection activities in the ecological conditions of the Dnipro Steppe in Kryvyi Rih industrial district.

2. Methodology

Kryvyi Rih District is a territorial division of the land of geographical zoning in Ukraine. The district is located in the south-east of the Central part of Ukraine. More than 90 % of its area is administratively located in the southwestern and western parts of the Dnipropetrovsk region. Only in the north-west of the district, it borders the Kirovohrad region, in the south – with the Mykolaiv and Kherson regions. Geographic coordinates of the study area are from 48°19′ to 47°28′ south latitude, from 32°58′ to 33°47′ west longitude. The area of the territory research district is 4.1 thousand km^2, which is equal to 0.67 % of the entire area of Ukraine. The length from north to south is 96 km, and from east to west is 62 km. The research areas are located in the basin of the middle course of the Ingulets River and its tributary, and partly in the east of the Kamianka River, which flows into the Dnipro River. According to the geological and metallurgical zoning of Ukraine, the territory of the Kryvyi Rih District corresponds to the territory of the Kryvyi Rih Iron Ore Basin (Kryvbas). Its subsoil contains unique iron ore deposits, which led to the construction of reach mining and industrial plants in this region.

These industrial enterprises dominate the structure of the region's economy in terms of the volume of manufactured products [1, 23, 24].

Woody ecosystems that are in favourable ecological conditions in relation to the city of Kryvyi Rih are represented by the natural stands of the Hurivka village forest (3 sites with natural and artificial tree vegetation are located in the floodplain of the Bokovenka River and on the territory of forestry); Valove village forest (woody ecosystems in the vicinity of the village Valove, 3 sites with natural and artificial tree vegetation are located in the floodplain of the Bokova River, Kryvyi Rih district, Dnipropetrovsk region); Tarasivka village forest (forest massif in the vicinity of the village Tarasivka, 3 plots of natural and artificial origin Sofiivka district, Dnipropetrovsk region). They were formed with the dominance of oak trees (Quercus robur L.), the estimated age of which is 180–80 years.

Forest ecosystems growing in relatively moist conditions and formed as sanitary water-protective tree ecosystems in the territories of the city of Kryvyi Rih are presented: Arboretum "Veseli Terny" (5 plots located in the northern part of Kryvyi Rih, floodplain of the Saksagan River); Water protection plants of the Karachuny woter Reservoir (5 sites located in the southwestern part of Kryvyi Rih, floodplain of the Ingulets River); Water, noise and dust protection plantations of the "Artem-1" mine tract (3 sites located in the central part of Kryvyi Rih, floodplain of the Saksagan River); dendrological park "Dovhyntsivskyi" (11 plots located in the eastern part of the Kryvyi Rih city, floodplain of the Saksagan River). It should be noted that Kryvyi Rih forest phytocenoses function in relatively not favourable ecological conditions. Forest ecosystems of water protection woody plantations are of both natural and artificial origin, aged 120-40 years; woody ecosystems of the Dovhyntsivyi Arboretum (2 plots) and the water protection plantations of the Karachunivyi Reservoir (5 plots) belong to the zone with unfavourable ecological conditions for the growth and development of woody plants. They are formed with the participation of Quercus robur L., Fraxinus excelsior L., Robinia pseudoacacia L, Quercus rubra L., Tilia cordata L., Pinus sylvestris L.. All woody plantations of this ecological zone are of exclusively artificial origin and were created approximately 50-80 years ago.

Sanitary dust-protection and noise-protection woody plantations are of artificial origin, 90-60 years old and located in the zone of unfavourable ecological conditions, represented by tree plantations of the urban and sanitary-protective woody belts (6 plots, tract of Dnipropetrovsk highway, "Kiltse Kosiora", the territory of "Arcelor Mittal Kryvyi Rih"). The woody plantations are dominated by Quercus robur L., Fraxinus excelsior L., Acer negundo L., and occasionally Ulmus laevis L.. It should also be noted that the edaphic conditions are characterized by a low level of moisture (except for the plantations of plot 1 due to flooding with technical waters of "ArcelorMittal Kryvyi Rih") and very significant aerogenic pollution due to the closeness of their territory to the city's mining and metallurgical enterprises.

During the research, cartographic materials from Internet resources GoogleMaps and lk.ukrforest.com were used. The analysis of the typological structure of forests was carried out according to the methods of the Ukrainian school of forest typology [1, 23, 24, 28–30]. Data analysis was carried out using MS Excel 2010 software.

The woody ecosystem's vitality was investigated and measured by such indicators of wood as the area of tree plantations, stock of wood, age structure of wood, distribution of diameters of tree trunks, presence of dryness, composition of tree species and consequences of harmful effects of environmental agents [1, 28–30].

Arithmetic average indicators of the vitality of the tree stand are considered by specialists to be the main characteristics of the statistical population of all taxa in the areas reflecting the level, in order to determine the fluctuation of variations in plant diversity. This statistical indicator in our studies took into account not only the visual averaged indicators of woody and shrub ecosystems, but also the characteristics of each individual plant on the site. A total of 39 key stationary research sites were worked out and measurements were made of 1.939 tree plants. Calculations of the vital state of tree and shrub ecosystems in accordance with ecological conditions were calculated on the statistical indicators of the arithmetic mean (M), taking into account the absolute error of the mean (m), the coefficient of variation (V) according to the number indicators [1, 28–30].

The obtained materials and results were processed by the method of variable statistics at the level of significance P>0.05 [13, 14, 29–31].

3. Results and discussion

The climate of the steppe zone is moderately continental. The annual radiation balance varies from 4100 (in the north) to 5320 Mj/m^2 (in the south). Thanks to this, the steppe zone has the largest thermal resources. Average annual air temperatures change from the northeast to the southwest from +7.5 to +11 °C. Average temperatures in July increase in the southern direction from +21.5 to +23 °C. Annual precipitation decreases from 450 mm (in the north) to 350 mm (in the south). A characteristic feature of steppe landscapes is high evaporation (from 700 to 1000 mm). According to climate studies, over the past 5 years, an increase in annual temperature by 0.6 ± 0.20 C/100 years and a slight increase in annual precipitation (5–7 % per 100 years) have been noted in Ukraine. The scientific works of climatologists also investigate the peculiarities of the transformation of seasonal changes in the climatic boundaries of the territories of Ukraine in terms of temperature and atmospheric precipitation [5, 12, 23, 24, 32].The Kryvyi Rih climatic conditions reflect the changes in the climate of the Dnipro Steppe and Ukraine as a whole. Plant ecosystems clearly respond to global changes in temperature regimes. In general, natural and artificial forest ecosystems are the most powerful factor in stabilizing the functional organization of natural ecosystems and strengthening their resistance against anthropogenic influence and regional climate changes. Forest ecosystems are able to significantly reduce the harmful anthropogenic impact on climate change in the region.

The steppe zone on the territory of Ukraine is relatively young. There is an opinion that the front of the steppes was an ancient forest-steppe zone. The relief of the Ukrainian steppes is flat, but heterogeneous. Due to insufficient humidification of the atmosphere, the density of the river network is insignificant: 0.08-0.05 km/km^2. Runoff is formed due to melted snow water. In the woody ecosystems of the territory of the Middle Dnipro region, which includes natural and artificially formed woody ecosystems on the Dnipro steeps, in the rafter-beam systems and on the floodplain of the Dnipro River in the Forest Steppe of Ukraine, experts distinguish 62 types of forest, among which fresh oak-primary forests predominate subir (68319.9 ha, 27.18 %) and hornbeam forest (32871.8 ha, 13.08 %), slightly smaller areas are occupied by fresh pine forest (17568.3 ha, 6.99 %), hornbeam-oak-pine forest (16952.2 ha, 6.74 %), maple-linden forest (15144.4 ha, 6.03 %), hornbeam- pine (13775.4 ha, 5.48 %) and hornbeam (9334.3 ha, 3.71 %) forest stands, as well as dry maple-linden oak forest (12810.9 ha, 5.10 %). The species composition of forest-forming species is quite diverse and is represented by 71 species of woody and shrubby plants. [25]. The main forest-forming species are Pinus sylvestris (116592.9 ha, 46.39 %) and Quercus robur (60049.7 ha, 23.89 %). Robinia pseudoacacia (26406.0 ha, 10.51 %), Alnus glutinosa (11391.7 ha, 4.53 %) and Fraxinus excelsior (7835.5 ha, 3.12 %) occupy somewhat smaller areas. All other species occupy small areas [25]. Identifying all the diversity of the forest ecosystem, both natural spontaneous overgrowth and artificially planted woody plantations, will provide an opportunity for specialists to plan directions for preservation, reproduction and protection of phytodiversity. Separately, experts note the importance of establishing the number of sozophyte species included in various protection lists. Another direction of research is the provision of balanced ecosystem services of a recreational and educational nature for the preservation and reproduction of woody plantations in the Middle Dnipro region [12, 22, 25].

Steppe landscapes in Ukraine territory were formed in a hot climate with a negative moisture balance. Studies of the current state of biodiversity of woody ecosystems in the territory of the Middle Dnipro Forest-Steppe of Ukraine, including in the Emerald Network, the forest typological structure of the ecosystems of the Middle Dnipro and the typological characteristics of hardwood stands of the Left Bank Forest Steppe are considered in the works of Ukrainian forest scientists [25, 33].

One of the most important characteristics of any ecosystem is its stability. The main parameters of a sustainable ecosystem are the constancy of the species composition, the closed cycle of substances and relatively constant bioproductivity [2, 6, 13–17]. The leading biological and dendrometric characteristics of artificial woody plantations have a clear environmental stipulation. In the Ukraine steppe zone indicators of the artificial woody plantations viability indicate a lack of moisture in the soil and an increased level of atmospheric pollution: pollutants constantly accumulated on the surface of leaves and the surface of the soil are significant ecological negative factors for all components of the ecosystem [4, 34].

Within the vast European forest territory, the values of the main vital indicators of tree ecosystems of artificial and natural origin show a significant range of variations due to changing natural conditions and anthropogenic influence. Taking into account such variability, it is very difficult to understand the correlations of indicators of the woody plantation's vitality, if they are separated from their ecological local origin [6, 17, 20, 21].

The implementation of the seven main pan-European indicators for the assessment of woody stands approved by the MCPFE for SFM, improves the process of monitoring the tree ecosystems state in monitoring studies of forest ecosystems. Among these seven main generally accepted indicators are: the area of woody plantations, wood stock, tree age structure, distribution of tree trunk diameters, presence of tree dry matter, composition of tree species, harmful agents, degree of adaptation and naturalization of woody ecosystems. Permanent monitoring of forest vital activity indicators requires obtaining national data by types of forest plantations of natural, naturalized and artificial origin [17, 19–21].

Structural organization of the forest stand. Taking into account that the basis of forest ecosystems is the soil cover of Kryvyi Rih district, which is represented by ordinary and southern chernozem with a high level of fertility. We classified soils under woody plantations as ordinary and southern chernozems; meadow chernozem soils; soils, which are less favourable for the growth and development of woody plant species, were classified as "dry" and "fresh"; "wet" and "moist" soils are also found in the region [1, 28].

The analysis of dendrometric characteristics showed that their optimal level is observed in the natural ecosystems of Hurivka village forest, Tarasivka village forest and woody ecosystems of the Volove village forest surrounding village's Volove. These woody plantations and natural forest ecosystems are in the most favourable ecological conditions for growth. The aforementioned ecosystems are characterized by a fully formed vertical structure of the tree stand. Thus, the natural density of the I-III tiers of tree and shrub plantations was 1175-1200 pcs./ha, their average height was from 14.9 to 19.7 and grew up to 22.5 m (I tier, 2020), the trunk diameter from 16.4 to 41.9 cm grew to 20.8 – 44.2 cm (I tier, 2020), the stock of trunk wood was from 383 up to 560 m^3/ha, the sum of cross-sectional areas 46 m^2/ha. The ratio between the I, II and III tiers of tree and shrub plantations is: 1.0:0.89:0.53 according to the averaged height indicators and 1.0:0.51:0.23 according to the averaged indicators of the trunk diameter. The dynamics of these indicators of tree vitality are calculated from 2015 to 2020. In general, indicators of the current state of the natural phytocenosis of the Hurivka village forest are optimal and can serve as a control in further research (table 1).

In the territories of the city of Kryvyi Rih ecosystems of sanitary water protection artificial woody plantation are characterized by a partially formed vertical tree structure, in some places there are no III tier shrubs or there is an insignificant amount of undergrowth. These ecosystems are located in the relatively favourable ecological conditions of Kryvyi Rih and are formed by

Table 1. Indicators of the woody plantation's structural organization.

Name of ecosystem	Density (trees/plot)	Density (trees/ha)	Height (m)	Diameter (cm)
Woody plantations in the Hurivka village	48.01±0.03	1200.03±0.03	19.71±0.13	18.11±0.04
Woody plantations in the Valove village	47.01±0.03	1175.01±0.03	14.87±0.18	16.42±0.01
Woody plantations in the Tarasivka village	45.01±0.02	1180.01±0.02	17.02±0.15	17.51±0.06
Arboretum "Veseli Terny"	90.02±1.18	2250.01±1.18	15.98±0.21	28.70±0.41
"Artem 1" mine Water-resistant woody plants	77.03±1.13	1925.0±1.131	17.18±0.24	26.87±0.43
Karachunivsky Water protection woody plants	401.02±1.15	10025.01±1.15	11.33±0.21	12.14±0.44
Arboretum Dovhyntsivsky	522.01±1.16	13050.01±1.16	12.43±0.24	17.67±0.48
"Kiltse Kosiora" dust-proof woody plantings	166.04±1.47	4150.01±1.47	16.51±0.24	10.23±0.46
Dnipro Highway dust-proof woody plantings	60.01±1.44	1500.03±1.44	14.07±0.27	21.01±0.42
"Arcelor Mittal KR" dust-proof woody plantings	170.01±1.48	4250.03±1.48	9.95±0.22	9.77±0.51
Arithmetic average indicators	162.61	4070.53	14.90	17.84

the dominant I-II tier of representatives of the species Quercus robur L., Fraxinus excelsior L., Ulmus laevis Pall. In addition, invasive plants Acer negundo L., Acer campestre L., Populus alba L., Acer platanoides L., Ulmus glabra Hudson, Morus nigra L., Salix fragilis L., Acer tataricum L. are also present in the III tier of these ecosystems. The woody ecosystems of the Dovhyntsiv Arboretum and the Karachuniv Reservoir belong to the zone with relatively unfavorable ecological conditions for the growth and development of woody plants. It should be emphasized that the vertical structure of these forest phytocenoses is not formed, with poorly developed II and III tiers, as well as a practically absent shrub tier. The herbaceous layer was also insufficiently pronounced at all monitoring sites. In the studied artificial woody and shrub plantations with a sufficient level of moisture and relatively favorable ecological conditions, the average density of plantations of the I, II and III tiers is 1925-13050 pcs./ha, the height was from 11.3 m to 16.0 m (I tier, 2015) and grew up to 18.3 m (1st tier, 2020), trunk diameter – from 12.1 cm to 39.6 cm (1st tier, 2015) grew to 41.7 (I tier, 2020). At the same time, the stock of wood in plantations ranged from 993 to 1912 m^3/ha, and the sum of cross-section areas was 32-36 m^2/ha. The ratio between the I, II and 3rd tiers of tree and shrub plantations is different from the control: according to the average indicators of the height of the trees it is 1.0:0.85:0.31 and according to the average indicators of the diameters of the tree trunks – 1.0:0.6:0,23 (for 2015-2020).

In sanitary dust-absorbing and noise-reducing tree and shrub plantations, the vertical structure of the woody ecosystems in these areas is determined by the well-formed I and II tiers and the underdeveloped III tier, as well as the practically absent shrub tier. There is almost no grass layer in the areas. In the studied artificial woody plantations located in dust-protection sanitary zones of the city with insufficient levels of moisture and unfavorable ecological conditions, the density of plantations of the I-III tiers is from 1500 to 4250 pcs./ha, height from

10.1 to 16.5 m (I tier, 2015) grew to 17.8 m (I tier, 2020), trunk diameter from 9.8 to 39.7 cm (I tier, 2015) grew to 41.5 cm (I tier, 2020), the stock of wood is from 380 to 813 m^3/ha, the sum of cross-section areas is 28 m^2/ha. The ratio between the I, II and III tiers is significantly different from the control, in particular, according to the average values of tree height, it is 1.0:0.88:0.6, and according to the average values of tree trunk diameters, it is 1.0:0.7:0.13 (for 2015-2020, figure 1).

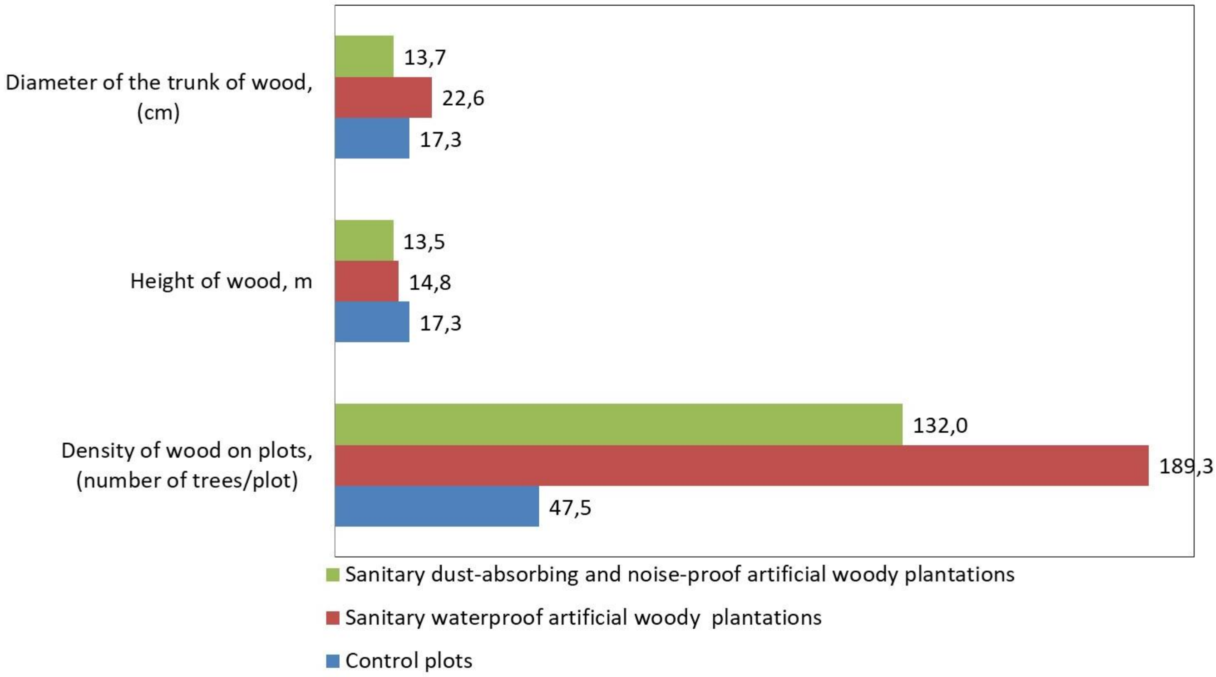

Figure 1. The average value of indicators of the structural organization of the state of trees (I-III tier) in the experimental plots.

Since 2021, access to the territories of research plots and sites has been partially or completely restricted due to military operations within the district or for security purposes. Thus, woody ecosystems were in relative isolation for 2-3 years.

In the territory of the Kryvyi Rih district factors regulating the density of tree and shrub populations of artificial and natural origin can be divided into dependent and independent of the density of tree plantations. Density-dependent factors including biotic factors transform with changes in the density of tree stands during their growth [4, 7, 35]. The study of the dynamics of the number of plants, taking into account pan-European indicators, for Sustainable Forest Management, improves the process of monitoring the state of tree ecosystems on the territory of the Dnipro Steppe. Thus, the investigation of seven main indicators can realize a comprehensive assessment of woody vitality to identify the key factors of the influence of the external environment on the homeostasis of an individual plant and the stability of the all ecosystem.

4. Conclusions

Therefore, the majority of tree ecosystems support the homeostasis of the population of dominant tree species, i.e. preserve the average number (the density is equal to 4070.50 trees per hectare) of artificial plantations of KKryvyi Rih district. Fluctuations in the number of woody and shrubby plants depend on a number of environmental factors – the speed of tree recovery, drying and removal, invasions of aggressive species, for example, such as Acer negundo L., Robinia pseudoacacia L., Acer campestre L., Populus nigra L..

The highest density of artificial tree plantations is noted on the territory of the Dovhytsivo Arboretum (13050.00 trees/ha) and the Karachuniv waterproofing tree plantations (10025.00 trees/ha), which is due to a complex of factors such as a good location in the terrain and a sufficient level of moisture. But the average indicators of height (14.83±0.24m) are not marked by an advantage compared to natural conditionally control plots. In each of the research plots, key influencing factors can be identified, such as the type of soil, insolation, moisture, temperature, the resistance of species to pests, distance from sources of industrial emissions, etc.

Such factors determine the direction of the further development of an individual woody plant and affect the growth of wood, the level of die-off, invasions of aggressive tree species, and changes in the species composition of the ecosystem.

It is also necessary to pay attention to the relatively high-density indicators of artificial forest plantations “Arcelor Mittal KR” 4250.00 trees/ha and “Kilce Kosiora” 4150.00 trees/ha due to the settlement of the III-rd tier. This tree layer consists of aggressive invasive species. However, these plantations are characterized by the smallest height (13.51±0.24m).

In perspective for order to assess the effects of abiotic factors, taking into account global features, it is necessary to develop regional scenarios of gradual changes in climatic conditions that will affect the tree ecosystems of Kryvyi Rih district locally and Steppe Dnipro regionally, namely temperature and precipitation fluctuations on this territory in Ukraine until 2050.

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Geospatial database generation of forest growth using the QGIS software package

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Geospatial database generation of forest growth using the QGIS software package

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Abstract. This article discusses the use of machine learning methods in the QGIS software package to create a geographic information database of forest growth. The authors explore the possibilities of applying machine learning algorithms to analyse satellite images of different resolutions and geospatial data to determine the growth of forest resources. The authors consider classification and forecasting methods and their advantages in the context of creating a database for tracking and managing forest resources. The research results confirm the effectiveness of using machine learning in QGIS for accurate and automated analysis of the dynamics of changes in forest cover, which can serve as a basis for decision-making in the field of forestry and protection of natural resource potential.

1. Introduction

At the current stage of technology development, space-based forest observation is becoming an increasingly attractive area of scientific research. This approach allows obtaining meaningful information about the condition of ecosystems, identifying the dynamics of their development and responding to potential threats in a timely manner. In this context, our study is aimed at analysing the Slobozhanskyi National Nature Park in Kharkiv region, which represents a complex territorial structure. It is important to analyse the effectiveness of satellite imagery in identifying and classifying tree species in this region.

As part of the study, we have selected block 1 of the park and will use high-quality satellite imagery to determine the optimal time to recognise different tree species in the area. To achieve this goal, we plan to use machine learning methods, which will allow us to systematically analyse and classify the data using the QGIS OrfeoToolbox provider plug-in.

It is important to note that the quality and volume of input data, as well as the choice of the optimal learning method, can significantly affect the results of our study. Therefore, our study will include an analysis of qualitative and quantitative data parameters, as well as a comparative analysis of different machine learning methods' effectiveness.

2. Literature review

The use of machine learning algorithms to analyse satellite imagery and geospatial data allows for more accurate and comprehensive data on forest growth, which can be useful for effective forest management and decision-making in the field of forestry in particular and the entire ecosystem of the region as a whole [1].

Loiola et al. [2] considered the use of machine learning algorithms to classify forest types. Optimisation of the forest management process is looking for alternatives that make data collection possible. One of these alternatives is spectroradiometry, which consists of measuring the spectral response, having as a product the target response in different wavelength ranges.

Bychkov and Popova [3] investigated the possibility of using Forest Landscape Models (FLM) to predict forest change at the landscape level. FLM initialisation usually requires detailed data on tree species and age; hence, in the absence of forest inventory data, it is very difficult to collect initial data for FLM. In this study, the authors propose a method of combining open source data, including remote sensing data, to address the lack of initial data and describe the initialisation of the LANDIS-II model.

Scientists [3,4] considered one of the most important principles of the natural reserves effective use, in particular functional zoning. The main task to be solved in the functional zoning of the territory is to study the peculiarities of the spatial distribution of natural complexes and anthropogenic pressure. Suska et al. [4] offer a promising scheme of functional zoning of the Homilsha Woods National Nature Park. When planning the functional zoning of the NNP territory and establishing the boundaries of functional zones, the priority criterion was to preserve the phytocoenotic diversity of vegetation, especially the presence and distribution of typical and rare plant groups listed in the Green Book of Ukraine.

Grinand et al. [5] conducted a multi-temporal analysis of Madagascar's dry forests. The area of lost forests was estimated from 2000 to 2010 using remote sensing methods and open source software (QGIS).

Bhunia et al. [6] investigates and tests the use of open geospatial data and software for collecting real-time remote sensing data for forestry management, and notes the high prospects of this area of information acquisition and analysis. It is noted that products such as QGIS (free and open source) have eliminated the need for licensing and data acquisition, which was a significant barrier to wider participation in mapping, tracking and modelling of forest resources for local authorities. At the same time, it is noted that there is a need to provide special access to high-resolution remote sensing data for conservationists, scientists and researchers in the field of environmental management.

Rao et al. [7] analysed the feasibility of using remote sensing and GIS to create input data for the preparation and implementation of a number of forestry activities, followed by the use of geospatial databases in sustainable forest management. It has been demonstrated that the generation of forest type maps; treatment maps; stock maps; boundary updates, separation of felling rows and groups, and assessment of site suitability for silvicultural practices and soil and moisture conservation can be achieved quickly and with much greater accuracy than other traditional methods.

Digital technologies are used not only to monitor forest resources but also water resources. You can use methods developed for the study of other objects. For example, digital water quality monitoring is an important part of modern efforts to conserve and manage water resources. It involves the use of a variety of technologies, such as sensors, satellite sensing, geographic information systems and other digital tools, to collect, process and analyse water quality data [8]

3. Methodology

The study was conducted on the territory of the Slobozhansky National Nature Park. The location of quarters and boundaries of different tree species can be seen in figure 1. The data is

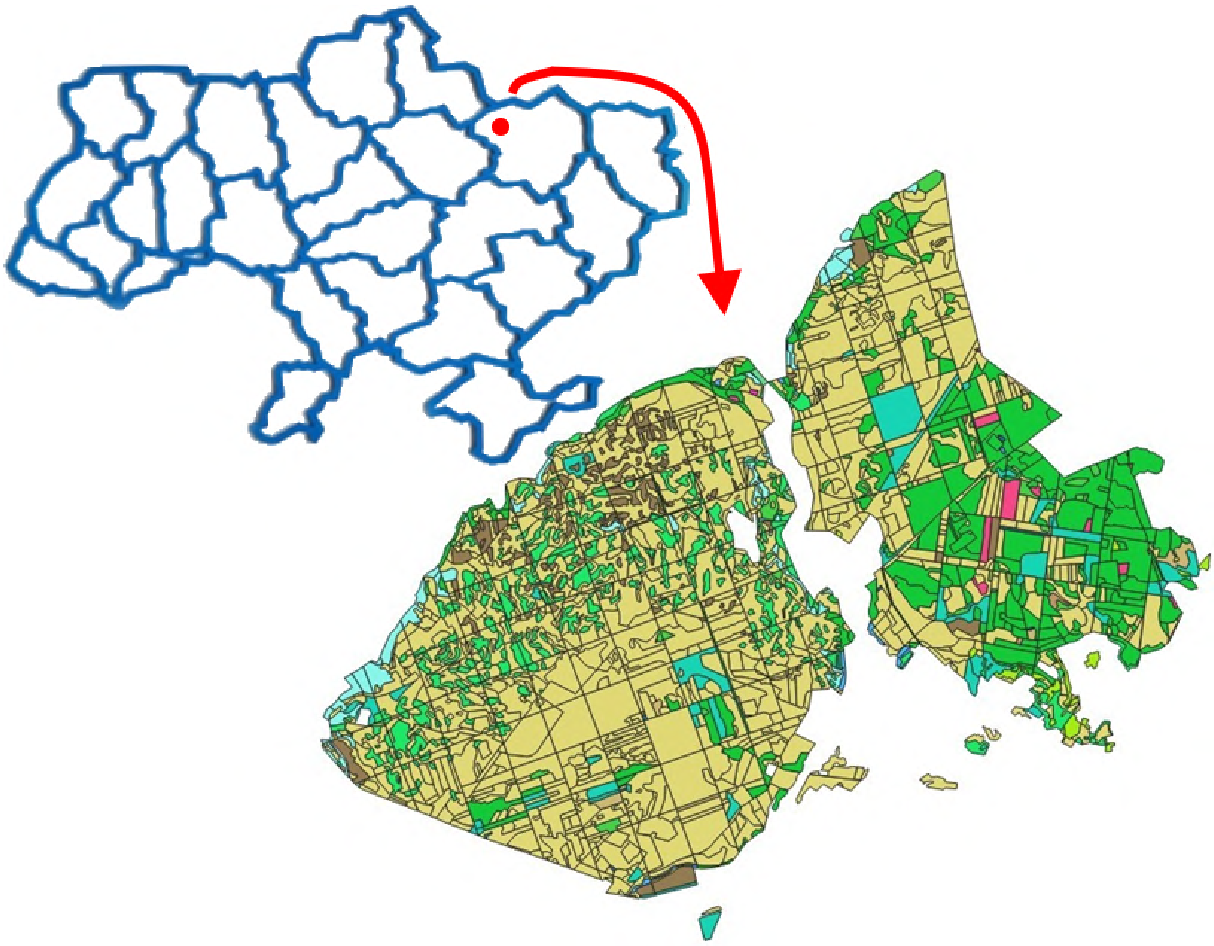

Figure 1. Slobozhanskyi National Nature Park, vector view.

presented in vector form using the QGIS software. The park is located in Kharkiv region near the town of Krasnokutsk.

Figure 1 shows that the territory of the National Park has a variegated structure, which makes it difficult to identify forest cover. According to the data, the park is divided into 127 quarters. For our experiment, we selected information about quarter 1, which is shown in figure 2. We downloaded three high-resolution satellite images from open sources for different years and months. This will allow to identify the time period most suitable for recognising tree species.

As you can see from figure 2, the satellite images differ, and this is especially evident in the 2018 image of April, when the trees are still without leaves. The exact tree species in the park is indicated in the semantic information (parameters) in the vector layer of the database. For quarter 1, figure 2 shows the following tree species: Scots pine (red areas), common oak (blue areas) and hanging birch (green areas).

Nowadays, the use of satellite imagery to study forests is becoming increasingly common. Thanks to the latest technologies and satellite data collection systems, we are able to study the state of forests in detail, detect changes in their cover and respond to threats to their ecosystems in a timely manner. However, the success of these studies depends heavily on the quality and relevance of the input data used.

One of the key aspects of using satellite imagery for forestry research is to determine the

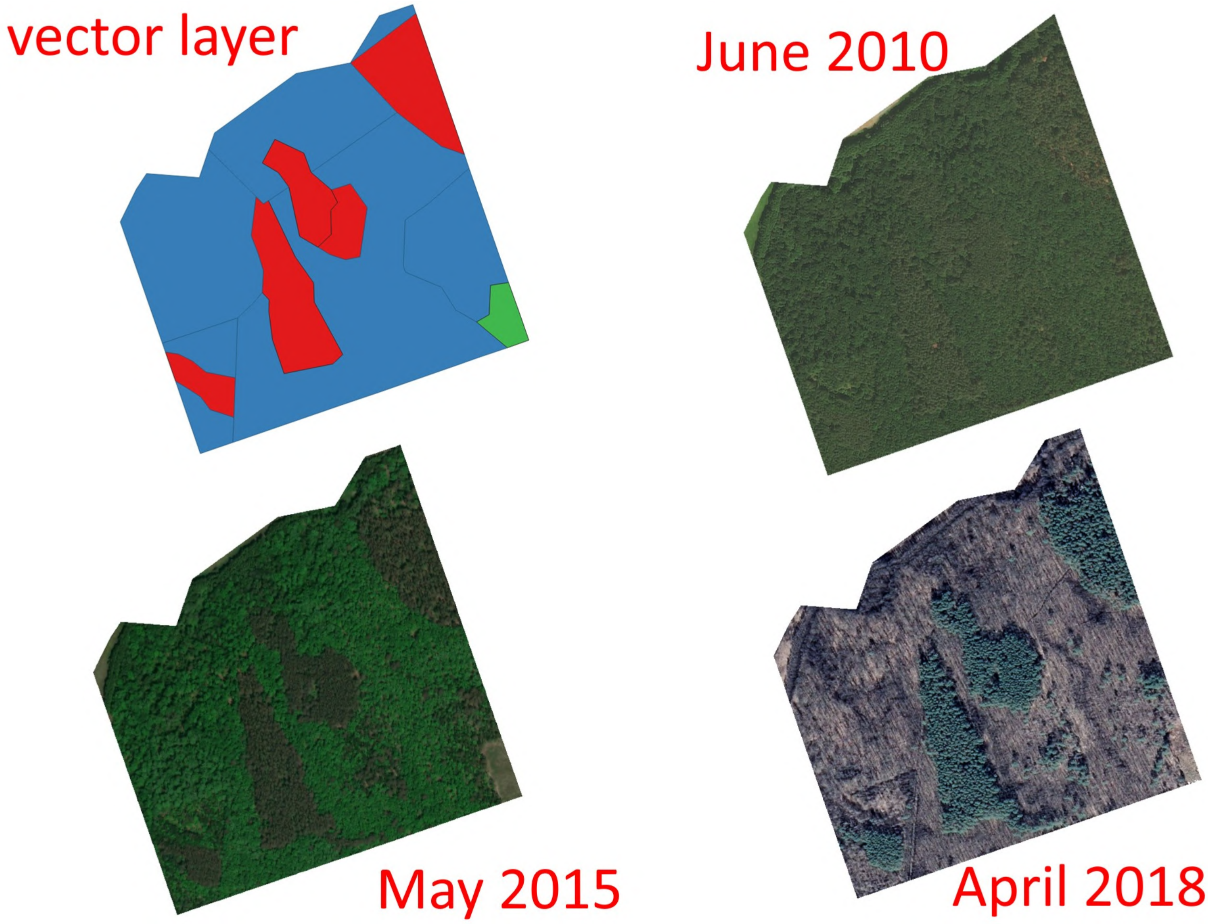

Figure 2. Quarter 1 of the Slobozhanskyi National Nature Park.

exact geolocation and characteristics of forest areas. For this purpose, it is necessary to have access to high-quality satellite images that provide sufficiently detailed information on the relief, vegetation types, soil conditions and other parameters. An important condition is also the ability to obtain up-to-date data at regular intervals, which will allow detecting the dynamics of changes in forest ecosystems.

Moreover, processing and analysis of satellite imagery is an important step in working with it. In order to achieve the best results, it is necessary to use specialised software that allows to perform a qualitative analysis of the data obtained. An important condition is also the proper expertise and qualifications of the specialist involved in processing and interpreting the images.

However, even with high quality satellite imagery and the right software, the success of our research depends to a large extent on the input data we use. Inaccurate or outdated data can lead to inaccurate results and even cause serious errors in conclusions [9]. Therefore, an important prerequisite for the successful use of satellite imagery for forest research is to consider the relevance importance and the input data quality. This means not only selecting the right data sources and collection tools, but also thoroughly checking them for accuracy and relevance.

The next stage of the study is to perform machine learning to recognise different breeds using the QGIS OrfeoToolbox provider plug-in. This free software product allows you to apply methods such as Boost classifier, Decision Tree classifier, Normal Bayes classifier, Random forests classifier, KNN classifier, Shark Random forests classifier, Shark kmeans classifier.

Before choosing a machine learning method, you need to clearly define the problem statement.

What kind of data do you need to solve this problem? What are the characteristics of this data (size, type, quality, etc.)? It is important to determine whether you have enough objects to train the model or whether you will need to collect additional data. Depending on what kind of task you want to solve (classification, regression, clustering, etc.), you should choose the appropriate machine learning method. For example, methods based on decision trees, neural networks or support vector machines may be suitable for classification [10]. It's important to understand how the model works and how decisions are made, so you should choose a machine learning method that provides a clear interpretation of the results.

To start training, you need to specify a sample image with a known class. The sample size (the number of objects in the training set) can affect the choice of machine learning method. For example, deep learning methods may be suitable for large amounts of data, while classical statistical methods may be effective for small samples. In our study, we performed machine learning on three types of data: three plots of 314 m^2 each, three plots of 1256 m^2 each, six plots of 628 m^2 each. This way, we will check how the number and area of training areas affects the efficiency of image classification. Given that we have three images, three learning approaches, and seven methods, we obtained 63 classification results.

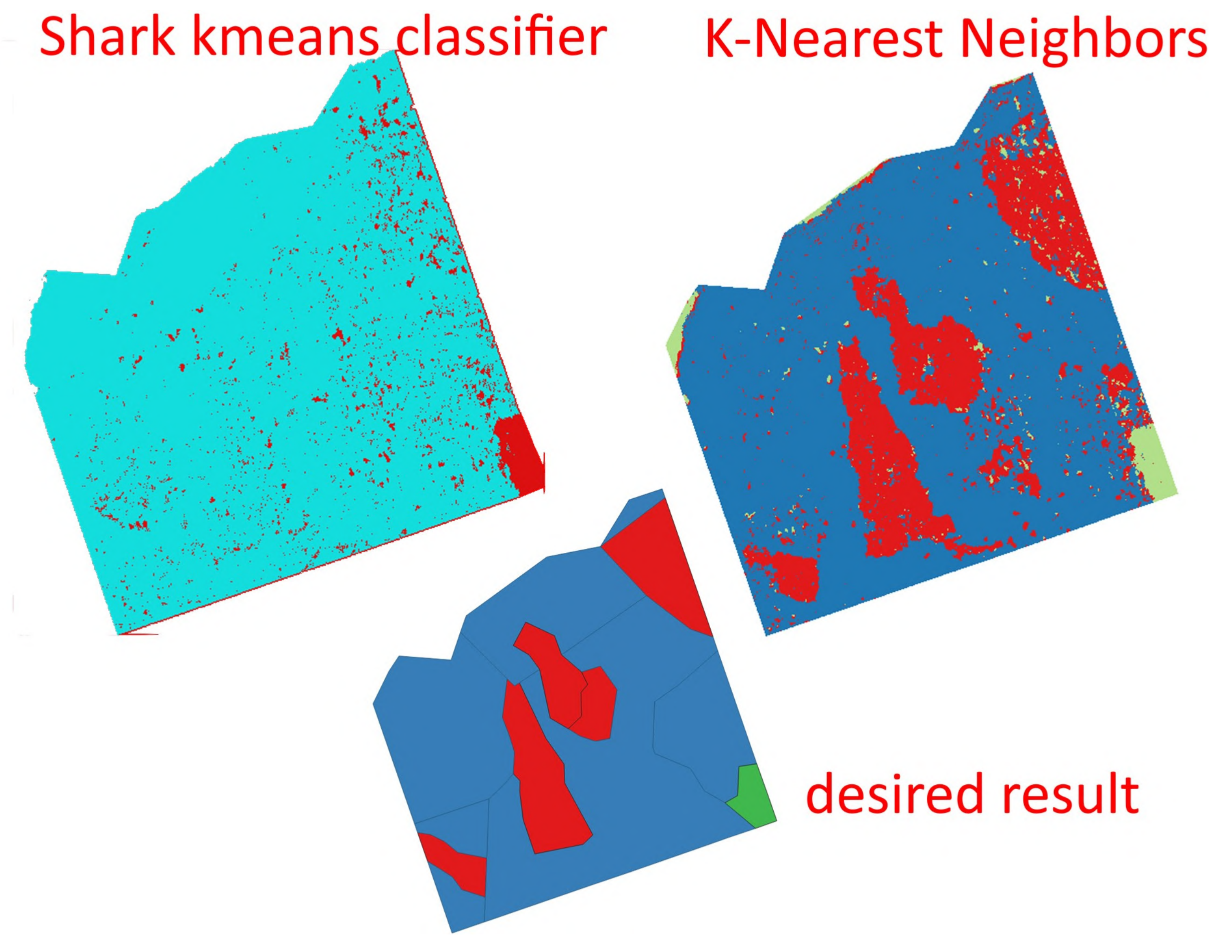

Figure 3. Comparing the results of different machine learning methods.

4. Results

The K-Nearest Neighbours method proved to be the most effective. The algorithm caches all training samples and predicts the response for a new sample by analysing a certain number (K) of the sample's nearest neighbours using voting, calculating a weighted sum, etc. This method is sometimes referred to as "learning by example" because it looks for a feature vector with a known response that is closest to the given vector for prediction.

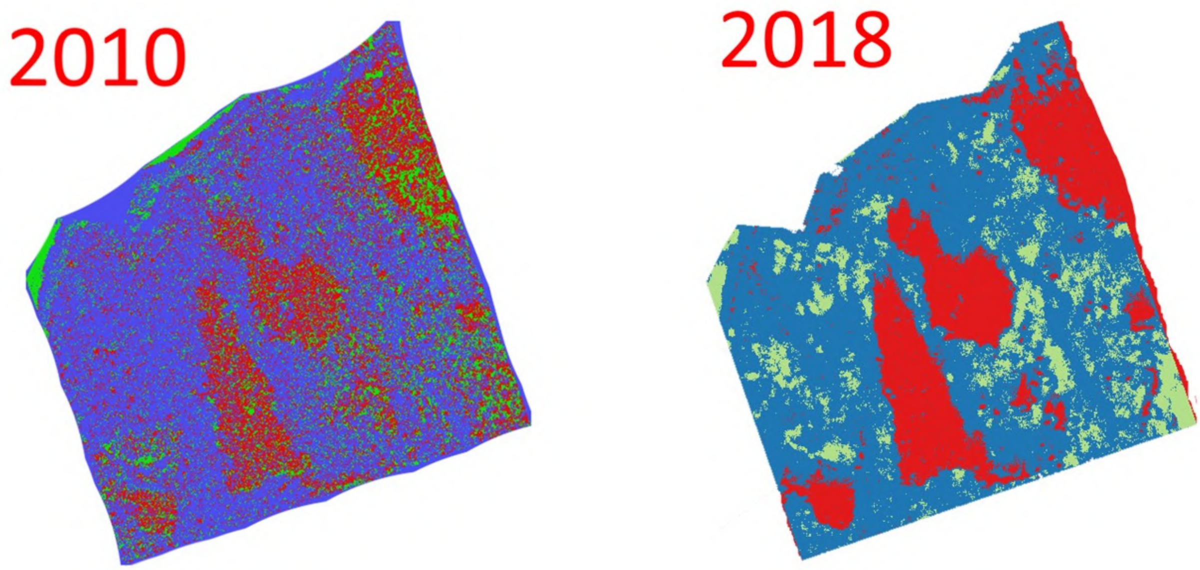

Figure 4. Comparison of satellite image classification results for different years and seasons.

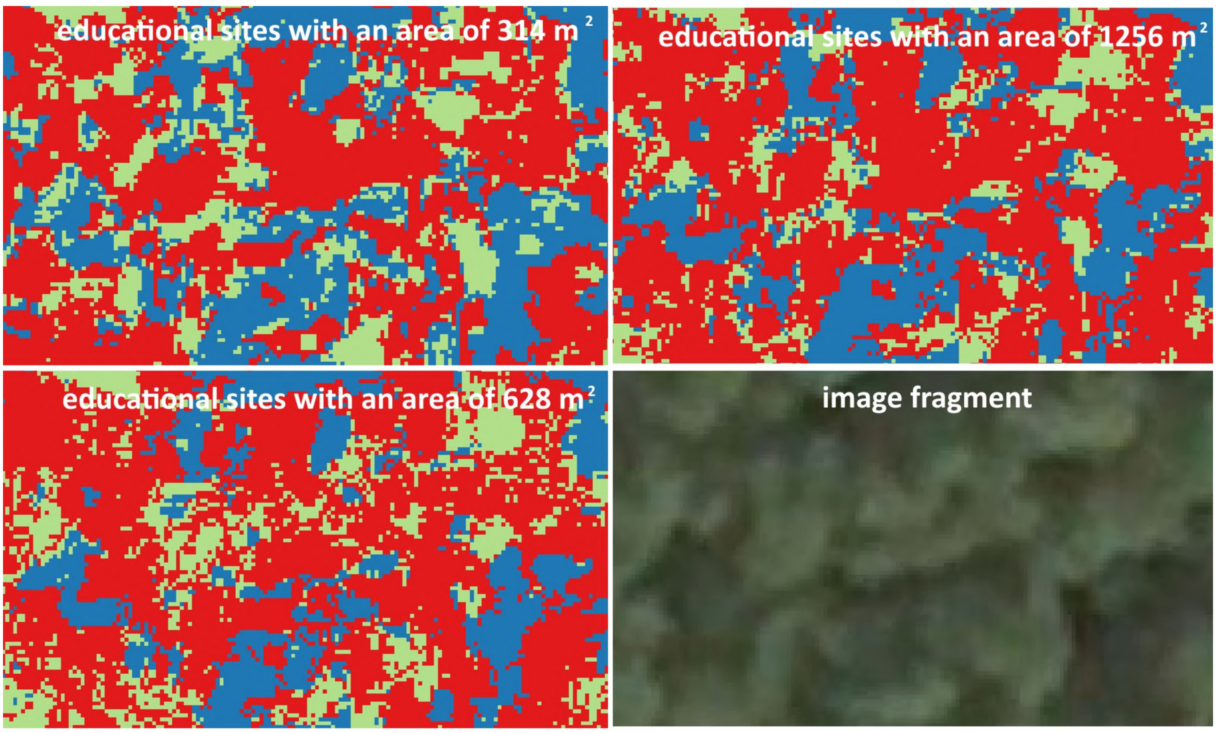

Figure 5. Visualisation of different approaches on the same image and with the same method.

An example of comparing the results of the K-Nearest Neighbours machine learning method with the Shark [11] k-means classifier method can be seen in figure 3. The same satellite image was used and the same training domain was used.

Figure 3 shows that K-Nearest Neighbours allows us to obtain a qualification result much better than from the same satellite image using other methods.

If we compare different images classified by the same method, we can see that the season of image acquisition is very important. Figure 4 shows the classification results for quarter 1.

As it is seen from figure 4, the date of image acquisition affects the efficiency of image interpretation. Depending on the type of tree species, the date of image acquisition should be selected. The information obtained should then be recorded in a single database. GIS software allows to combine and analyse different types of spatial data from different sources.

Not only does the resolution and time of acquisition (season) affect the quality of the classification, but also the amount and type of training the software receives to classify the image. Three different approaches on the same image and using the same method can be seen in figure 5.

Image classification is highly dependent on the selection of samples (objects) for machine learning. As it is seen from figure 5, the same fragment can be classified with different efficiency.

5. Conclusions

The use of machine learning to classify satellite images of forest resources allows to create and maintain up-to-date databases. Among a wide range of machine learning methods, you need to choose the one that will be most effective for identifying certain tree species. Combinations of methods may be used. Satellite imagery should correspond to the period when different tree species are very distinct and not blend into the background. It is necessary to take into account that trees look different in different seasons, i.e. biological features of the vegetation cover should be taken into account. Another condition for effective forest classification is the selection of the data amount to create a classification model (the learning program). There are no universal recommendations for this task. It is necessary to select an effective option in terms of area and fine contour by gradual approximations. The use of artificial intelligence in the form of machine learning allows the classification of satellite data, thereby ensuring the functioning of forest databases.

Thus, artificial intelligence in geographic information systems has great potential for solving complex tasks of analysing and processing geospatial data. At the same time, for the successful application of these technologies, it is necessary to address the issues of security, confidentiality and data availability. Taking these aspects into account, artificial intelligence in GIS can become a powerful tool for the development of various industries that use geospatial data.

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Areas of the nature reserve fund use in the context of sustainable development

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Areas of the nature reserve fund use in the context of sustainable development

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Abstract. The study is aimed at analysing the conditions and prospects of the nature reserve fund development of the Kharkiv region in order to develop recommendations for optimising the management and conservation of natural resources in the sustainable development context. The nature reserve fund is an important component of the sustainable development model, contributing to the conservation of biodiversity, maintaining the sustainability of natural ecosystems, environmental education and recreation. The article examines the problem of slowing down the formation pace of new territories and objects of the nature reserve fund (NRF) in Kharkiv region and in Ukraine as a whole, which is a consequence of the current socio-economic situation. The authors of the article believe that to solve this problem, it is necessary to amend the current legislation, in particular, to simplify the procedures for creating new NRF objects and to introduce economic measures to encourage land users and landowners to create such objects. It is noted that the existing protected area rate in Kharkiv region, although exceeding the average rate in Ukraine, is still lower than in neighbouring European countries. The problematic issues are compounded by the lack of a clear strategy for the development of protected areas and the lack of the management system coordination at the state and regional levels. To solve these problems, it is necessary to ensure the implementation of a set of measures, such as the creation of a scientifically based network of protected areas and objects and a system of balanced nature management. The article offers a set of measures to intensify the processes aimed at achieving Goal 15 in Ukraine, in particular, to intensify the work of local authorities to create new territories and objects of the nature reserve fund.

1. Introduction

Sustainable development is currently one of the most important challenges for humanity. The essence of "sustainable development" is to maximize economic and social benefits from the development of the national economy system while protecting the environment and ensuring the long-term reproduction of natural resources. In the economic sense, sustainable development means not only the growth of the national economy and an increase in per capita income, but also the improvement of all elements of social security. Sustainable development should be accompanied by the necessary structural changes in the environmental, economic and social spheres.

The term "sustainable development" was coined at the United Nations Conference on Environment and Development, where it was defined as the development of society that meets current needs without compromising future generations [1]. Since the 1990s, sustainable economic development has involved significant organizational and managerial efforts to achieve the 17 global goals and 169 targets of the new 2030 Action Plan, which came into force on January 1, 2016. The growing transboundary environmental impact and other negative consequences of human activity indicate the need to strengthen international dialogue on security issues and implement a unified global strategy in the process of transition to the principles of sustainable development.

The sustainable development model is based on three components: economy, environment and society [2–4]. The axiom of this model is that one component cannot develop without taking into account the others. For example, if only the economy is developed without paying attention to the ecosystem, an ecological catastrophe may occur, which will call into question the very existence of humans. On the other hand, uniform development of the economy, but without taking into account society, can lead to poverty and unemployment of a large share of the population, which will eventually lead to a demographic and economic crisis.

The nature reserve fund is an important component that contributes to the conservation of biodiversity, the sustainability of natural ecosystems, environmental education and recreation [5]. Currently, the world and Ukraine are actively implementing reforms in two key aspects: expanding the area of protected areas and expanding their functions and tasks. The main emphasis is on the transition from simple species conservation and limiting human interference in wildlife to establishing methods of coexistence between humans and nature, rational exploitation of natural resources, and sustainable development of territories and communities. The study is aimed at analysing the condition and prospects of the nature reserve fund of the Kharkiv region in order to develop recommendations for optimizing the management and conservation of natural resources.

2. Literature review

The issue of sustainable development strategies as the basis for the future quality of life of society was considered by Guerra et al. [6]. The analysis of socio-economic indicators in the context of sustainable development has been studied by Çağlar and Gürler [7] and Deveci et al. [8].

Deveci et al. [8] examined the importance of seventeen Sustainable Development Goals (SDGs) using a decision-making approach based on rough sets. This new approach consists of three consecutive stages, namely a questionnaire (survey), data analysis, and SDG classification. First, a survey is conducted to obtain responses from international experts from different countries. Each participant offers to assess the importance of each SDG. Second, an analysis is conducted to identify groups of participants who respond in the same way and to identify the views of academia and non-governmental organizations. The degree of importance of each SDG for sustainable development is determined using a new decision-making approach, including the Ordinal Priority Approach (OPA), based on approximate data sets.

The issues of the consequences of the implementation of the sustainable development goals are described by Bansal, Singh and Nangia [9] and Del-Aguila-Arcentales et al. [10]. The results of the study [9] identify the most influential articles and sources on the topic based on their publication, citation, and importance to the smart grid; in addition, the study sheds light on the intellectual structure of the subject (thematic analysis), which is supported by the main clusters focused on "environmental impact", "economic and social impact", "technological innovation and digitalization", and "circular economy". In [10], a partial technical analysis was conducted using a structural equation using the least squares method. It was found that social SDGs (0.796) and environmental SDGs (0.196) had a positive impact on economic SDGs.

In the article by Lacka and Brzezicki [11], the development of European countries in the context of global strategic planning is studied. Taking into account the sequential nature of the stages, a combined analysis of eco-efficiency, eco-innovation and sustainable development goals

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was conducted. The analysis was conducted for 27 EU countries in 2017–2019. The study used the SBM dynamic network and the Malmquist dynamic divisional index. The results of the study show that EU countries achieve relatively higher performance results in eco-innovation and SDGs than in eco-efficiency.

The experience of Poland's development in the context of the implementation of the SDGs is considered by Kasztelan [12]. The paper presents the results of assessing the implementation of the national sustainable development goals of Poland from 2010 to 2019. For this purpose, a synthetic index (National Sustainability Index) was developed using taxonomic methods. The study sought answers to the following questions: What is the overall level of Poland's achievement of sustainable development goals? What were the dynamics of changes in the relevant years? Which goals will require special attention and action in the coming years? Given the possible range of NSI, there has been a significant improvement in the achievement of the national sustainable development goals in Poland in the years under review. Nevertheless, some areas still require interventions at the decision-making level, which will further balance the paths of economic growth and development in Poland.

A number of Ukrainian researchers have examined the current problems of sustainable development of the country [13–15]. In particular, Rybak et al. [16] provides an example of bringing the territory of a biosphere reserve in line with international requirements for biosphere reserves; identifies the main areas of activity aimed at interaction between the administration of the Carpathian Biosphere Reserve and local communities and develops recommendations for the implementation of measures to ensure the creation of a transit zone of a biosphere reserve in Ukraine.

Riabtsova [17] discusses the general principles of nature management applicable to all subjects of law, as well as specific principles relating only to the use of natural resources in the field of economic law. The general principles include rational use of nature, the emergence of the right to use natural resources from the right of ownership, targeted use of natural resources, sustainability of the right to use nature, ecosystem considerations, integrated use of nature and free use of nature. Special principles of nature management, which are specific to economic entities, should include payment for special use of nature, restriction of nature use, licensing of nature use and greening of production, ensuring a balance between economic, social and environmental interests.

The article [18] is one of the first attempts to fill the existing gaps in the issue of the war's impact on protected areas. The article identifies trends in the development, current status and problems of the objects of the nature reserve fund of Ukraine in the context of Russia's unjustified full-scale military aggression, and provides an approximate calculation of the damage caused by hostilities.

Radchenko et al. [19] analyses the issue of forming a strategy for the development of the state through the prism of the state environmental safety, preservation of its natural capital in the process of forming and implementing the state environmental policy. The basic ecological, economic, and social principles of preserving the natural capital of Ukraine are considered. The possibilities of development of the ecological network of Ukraine are investigated and a comprehensive knowledge base for natural capital management is shown.

3. Results and discussion

Nature conservation and environmental protection are recognized as one of Ukraine's priorities in the context of European integration. The main structural element of the national territorial system of natural objects is the territories and objects of the nature reserve fund. They have been set aside for their unique environmental, scientific, aesthetic, recreational and other values in order to preserve the diversity of landscapes, the gene pool of animals and plants, maintain ecological balance and conduct background monitoring of the environment.

In the national legislation, the concept of "sustainable development" was first used in the Resolution of the Verkhovna Rada of Ukraine "On the Main Directions of the State Policy of Ukraine in the Field of Environmental Protection, Use of Natural Resources and Ensuring Environmental Safety" [20]. Section V "Main stages of implementation of the main directions of the state policy of Ukraine in the field of environmental protection, use of natural resources and ensuring environmental safety" states that "it is planned to create a system of state management of the use of natural resources, regulation of technogenic impact on the environment as a basis for managing sustainable development of society". One of the main tasks of this stage is "proper coordination of the rational use of natural and socio-economic potential, taking into account environmental factors on the basis of sustainable development".

One of the main objectives of the European Green Deal is to preserve and restore ecosystems and biodiversity. The EU is actively implementing transformational policies in this area, having already adopted the EU Biodiversity Strategy 2030 and the New EU Forestry Strategy 2030. The EU's goal is to cover at least 20 % of the EU's land and marine areas with nature restoration measures by 2030 and to restore all ecosystems in need by 2050.

Since 2015, when the UN adopted the 2030 Agenda and 17 Sustainable Development Goals [21], Ukraine's progress in their implementation has been uneven, with serious problems in achieving the vast majority of the SDGs. The implementation of the tasks to ensure the protection of ecosystems and biodiversity (SDG 15) has partially stopped (table 1)

Table 1. Dynamics of changes in the components of the Sustainable Development Goals Index of Ukraine, 2015–2021.

Goals	2015	2021	Growth rate 2021–2015, %	Goals	2015	2021	Growth rate 2021–2015, %
Goal 1	99.5	99.8	0.34	Goal 10	99.5	99.5	0.00
Goal 2	63.0	64.1	1.78	Goal 11	74.5	75.5	1.35
Goal 3	66.7	76.8	15.14	Goal 12	88.6	88.1	-0.53
Goal 4	80.9	80.2	-0.93	Goal 13	90.1	89.3	-0.86
Goal 5	64.4	67.7	5.15	Goal 14	64.8	73.4	13.21
Goal 6	79.0	78.8	-0.19	Goal 15	63.7	63.7	0.10
Goal 7	68.1	69.7	2.32	Goal 16	62.6	66.5	6.25
Goal 8	70.8	71.2	0.54	Goal 17	76.3	73.4	-3.76
Goal 9	23.0	49.3	113.95				

Russia's aggression against Ukraine has created numerous indirect challenges to its path to sustainable development, but it has not led to a halt to its aspirations for European integration and sustainable development. For example, the need for high-quality and timely data for effective decision-making has increased. However, today there are serious difficulties in collecting and processing economic and financial statistics, in particular in the context of the 2030 Agenda and assessing progress towards the SDGs. An important indirect impact is that military operations significantly distribute the government's organizational resources and impede coordination of actions under the 2030 Agenda. Even amid the war, Ukraine, which became a candidate for EU membership on June 23, 2022, has taken the first steps in this direction. In particular, it was decided to establish an Office for the Implementation of the Sustainable Development Goals. This office will be responsible for organizing the development and implementation of a mechanism for incorporating the SDGs into national and regional policies, strategies, and planning processes.

Assessments by international organizations and experts agree that the war and related economic problems have had a negative impact on sustainable development indicators across the entire list of SDGs in Ukraine. One of the central topics for discussion in the expert community is to identify the interrelationships between the various goals, targets and indicators within the 2030 Agenda. No country can achieve sustainable development without peace. Thus, Ukraine's regression in achieving the 16th SDG "Peace, Justice and Strong Institutions" is evidenced by the Global Peace Index, which decreased by 16 % in 2022 to 153rd place in the ranking (in 2021 it was ranked 143rd), demonstrating the worst dynamics among the 163 countries surveyed [23,24].

The implementation of the policy aimed at protecting and restoring terrestrial ecosystems, including the preservation and expansion of the territories of the nature reserve fund in Ukraine, has brought about certain positive changes, but unfortunately has not allowed for the dynamics necessary to approach the targets on the horizon until 2020. In particular y the area of territories and objects of the nature reserve fund in Ukraine increased (from 3803.13 thousand hectares in 2015 to 4173.2 thousand hectares in 2022) and the share of the area of territories and objects of the nature reserve fund in the total territory of the country (from 6.3 % to 6.76 %, respectively). However, such rates do not allow to achieve the target benchmarks – 6276.9 thousand hectares and 10.4 %, respectively. Due to the signing by the President of Ukraine of 15 decrees on the creation/expansion of territories and objects of the nature reserve fund, as well as other decisions at the national and local levels, the area of the nature reserve fund was increased by approximately 279 thousand hectares, or 0.36 % of the territory of Ukraine [25] (figure 1).

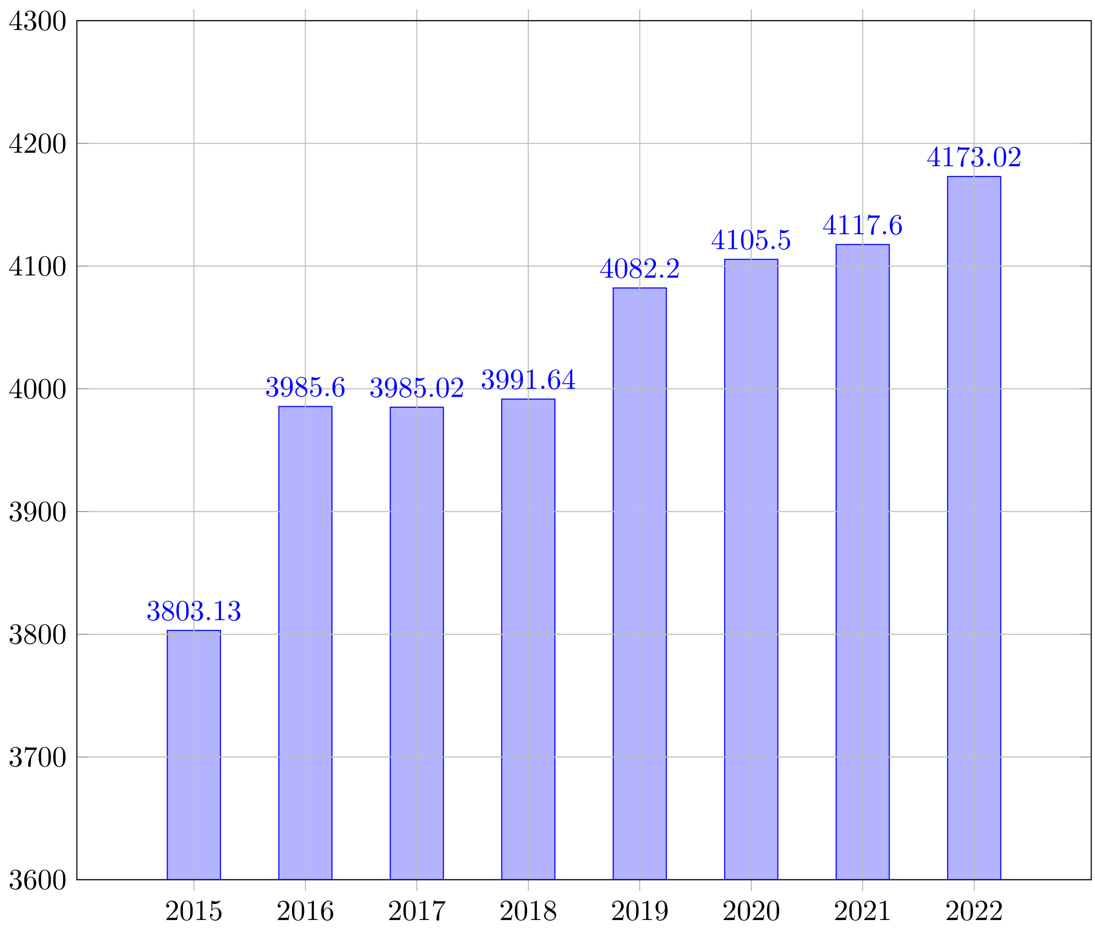

Figure 1. Area of territories and objects of the natural reserve fund, thousands of hectares [24].

One of the key current problems in the field of nature reserves funds (NRF) in Ukraine is the lack of clearly defined boundaries of nature reserves at the regional level and the unresolved issue of their introduction into nature, despite the existence of relevant decisions of the President of Ukraine and the Verkhovna Rada of Ukraine. The main reason for this is the lack of funding for the development of relevant land management projects, since the boundaries of NRF territories are determined only after the allocation of funds for their introduction into nature, i.e. after the creation of NRF territories, and not at the stage of their formation.

As of January 1, 2023, the nature reserve fund of Kharkiv region includes 247 protected areas, with a total area of 74.877 thousand hectares. Out of the total number, 13 nature reserve sites are of national importance and 234 are of local importance. The proportion of the area of the nature reserve fund in the area of the administrative unit is 2.4 %, which is one of the smallest in Ukraine, second only to Vinnytsia region [26].

According to Ukrainian legislation, as defined in the Law “On the Nature Reserve Fund of Ukraine” [25], there are two main categories of protected areas: natural and those created artificially in the form of collection and park objects. Natural territories include nature reserves, biosphere reserves, national nature parks, regional landscape parks, nature reserves, natural monuments, and protected tracts. On the other hand, artificially created objects include botanical gardens, dendrological parks, zoological parks, and parks-monuments of landscape art (table 2).

Analysing the dynamics of the structure of the region’s nature reserve fund from 2019 to 2022, we note an increase in the number of local nature reserves by 1 unit in 2021. During this period, at the initiative of the regional state administration, there were attempts to expand the lands of the region’s nature reserve fund, but no final decisions were made. We estimate that if measures had been taken to include the territory in the region’s nature reserve fund, which is 71450.5 hectares, the percentage of the actual area of the NRF to the area of the administrative unit would have been 4.65 versus the actual 2.4. Thus, as of 2022, the structure of the lands of the nature reserve fund of the Kharkiv region is shown in figure 2, where the national value is 28 %, local value is 72 %.

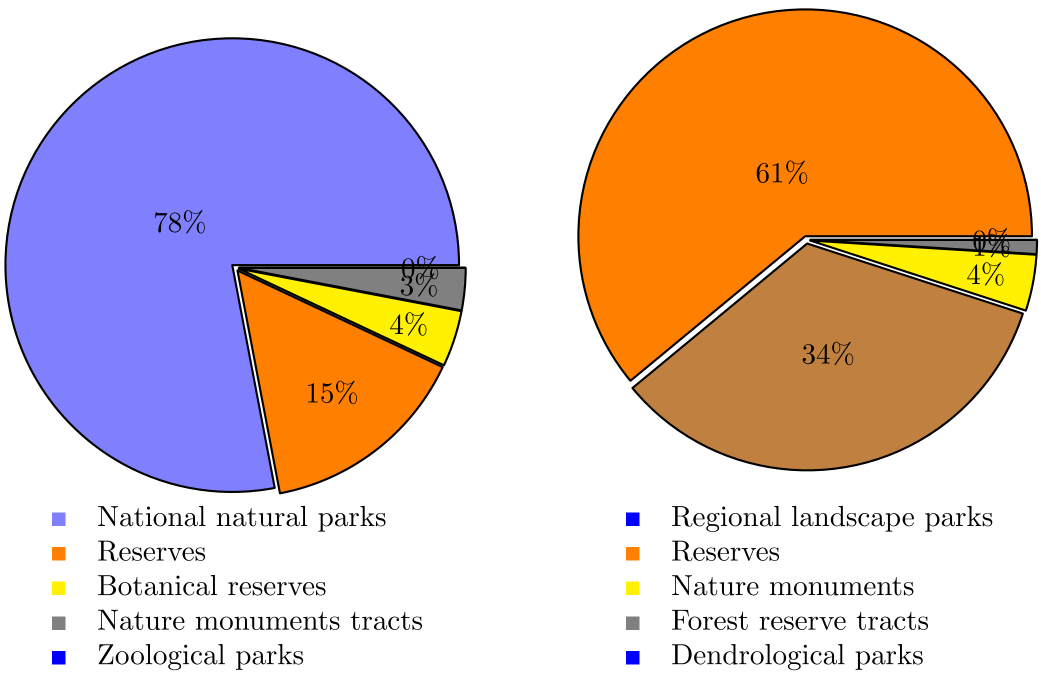

Figure 2. NFR structure in Kharkiv region as of 2022 [24].

Table 2. Dynamics of the nature reserve fund structure of Kharkiv region [24].

Categories of protected areas and NRF objects	2019		2020		2021		2022	
	Quantity	Size, ha	Quantity	Size, ha	Quantity	Size, ha	Quantity	Size, ha
National nature parks	3	22 690.0	3	22 690.0	3	22 690.0	3	22 690.0
Regional landscape parks	7	20 544.33	7	20 544.33	7	20 544.33	7	20 544.33
Nature reserves of national importance	3	1 038.0	3	1 038.0	3	1 038.0	3	1 038.0
Nature reserves of local importance	170	37 613.82	170	37 613.82	171	37 647.32	171	37 647.32
Natural monuments of local importance	44	645.9	44	645.9	44	645.9	44	645.9
Protected tracts	9	2 537.2	9	2 537.2	9	2 537.2	9	2 537.2
Botanical gardens of national importance	1	41.9	1	41.9	1	41.9	1	41.9
Botanical gardens of local importance	1	13.25	1	13.25	1	13.25	1	13.25
Dendrology parks of national importance	1	22.8	1	22.8	1	22.8	1	22.8
Dendrology parks of local importance	1	51.5	1	51.5	1	51.5	1	51.5
Zoological parks of national importance	1	22.0	1	22.0	1	22.0	1	22.0
Parks-monuments of landscape art of national importance	4	169.9	4	169.9	4	169.9	4	169.9
Parks-monuments of landscape art of local importance	1	10.8	1	10.8	1	10.8	1	10.8
TOTAL	246		246		247		247	
Actual NFR area		74 843.56		74 843.56		74 877.06		74 877.06
% of the actual area of NFR areas from the area of administrative units		*2.38*		*2.38*		*2.4*		*2.4*

The fact that the State Strategy for Regional Development until 2020 [27] stipulates that the amount of land in the nature reserve fund of Kharkiv region should be 282.735 hectares at the beginning of 2020, which is equivalent to 9 % of the total area of the region, indicates a low level of measures to increase the percentage of the region's territory reserved (figure 3). In other words, the percentage of territories allocated for the reserve fund does not meet the planned indicators.

Thus, there are certain difficulties in the process of creating new and expanding existing protected areas in Kharkiv region. Due to restrictions on the use of natural resources, the work on the formation of NRF is delayed. Most stakeholders, such as local governments, forestry

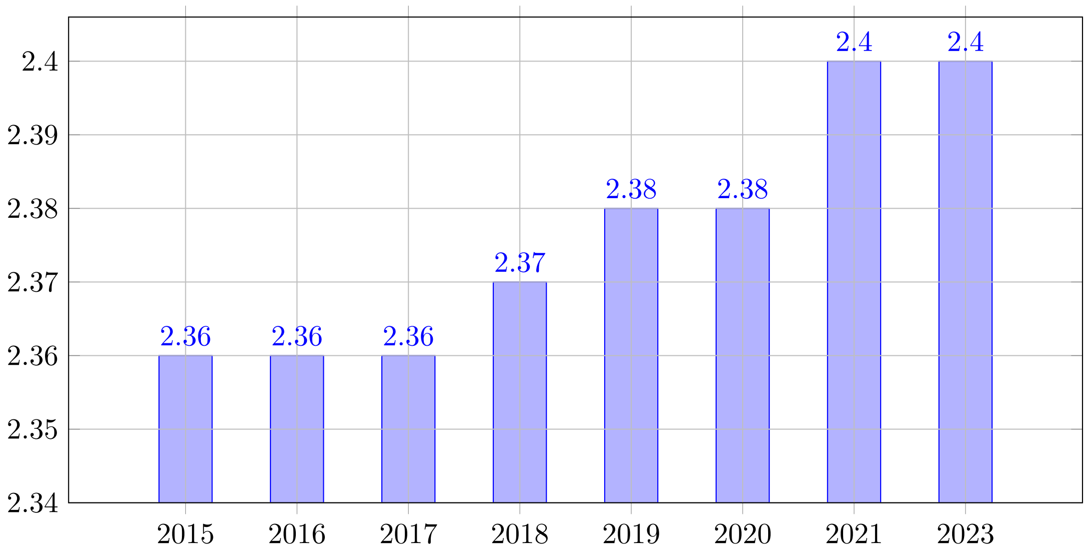

Figure 3. Dynamics of changes in the area of the nature reserve fund in Kharkiv region, % [24, 27].

enterprises, landowners and land users, do not agree to the creation of new or expansion of existing protected areas in the region. They justify their position with restrictions on nature management, restrictions on visiting the territory during certain periods of the year, restrictions on the activities of users of hunting grounds, as well as a ban on grazing and other aspects defined by the current legislation for protected areas. Ukrainian legislation in this area needs to be revised and adapted to European standards, especially with regard to taking into account the interests of landowners and land users in the process of including their land plots in the nature reserve fund.

There are certain disproportions and problems of nature management in the region's NRFs. In particular, the protected status of administrative districts is very uneven, with differences between them reaching dozens of times. Although after the administrative-territorial reform, the percentage of protected areas for new districts increased significantly, the percentage of protected areas in territorial communities remained at the level before the reform.

The perspective directions of development of the nature reserve fund of Kharkiv region can be represented by the following structural and logical scheme (figure 4). This logical structure can serve as a basis for the development and implementation of the strategy for the development of the nature reserve fund of the Kharkiv region.

One of the promising areas for increasing the area of land in the nature reserve fund of Kharkiv region may be at the expense of territories reserved for the creation of new or expansion of existing nature reserve objects, creation of ecological corridors, and land reclamation. In the current version of the ecological network of the Kharkiv region, only forest belts along the railways are included in the regional eco-corridors of artificial origin. In many districts of the Kharkiv region with moderately low levels of natural resources, it is forest belts with adjacent agricultural land that can optimize the structure of the adjacent territory. The design also fails to take into account that the proposed eco-corridors of natural origin of "local" significance do not ensure, first, the functioning of the region's ecological network as an integral system; second, a full-fledged connection between the biocenters of Kharkiv region and the biocenters of other regions (Poltava, Dnipro, Donetsk) [28].

Given the experience of Poland, it is the territories and objects of the nature reserve

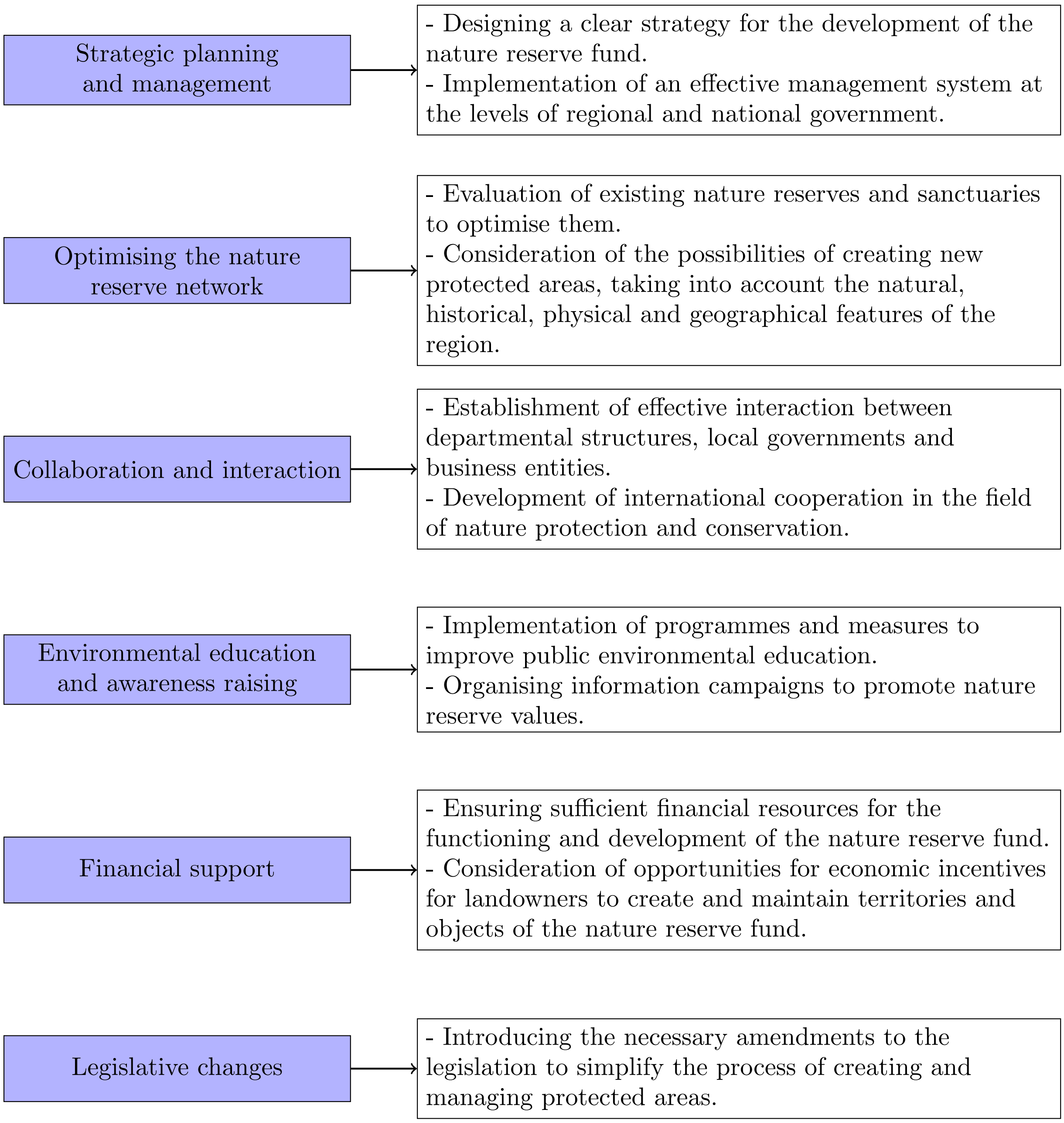

Figure 4. Structural and logical scheme of further development of the nature reserve fund of Kharkiv region.

fund that can disseminate information on their territories, in particular, within the areas of regulated recreation, on the existing ecological corridors that ensure migration of animals from this particular protected area. Each protected area that is a key territory should be assigned ecological corridors that connect the key territory with other areas in order to properly monitor the connecting areas for compliance with environmental legislation. It is also quite appropriate to work with local residents, explaining the benefits of the ecological network and the opportunities provided to local residents whose land plots are included in the ecological network [29]. In order to optimize the structure of the ecological network of the Kharkiv region, an additional category of ecological corridors can be identified, namely local ones, due to the boundaries of the beam and valley lands, where the vegetation has retained a relatively natural state and there is a limited anthropogenic load. Forest belts and watershed forests can become connecting areas between them, which makes it possible to promote the connection of existing ecological corridors.

For example, in the Krasnokutsk community of the Bohodukhiv district of the Kharkiv region, the inclusion of reserved areas in the lands of the community's ecological network will increase its area (the existing area of the nature reserve fund is 1091.6 hectares) and will amount to 11475.5 hectares, while the area of the nature reserve fund will be 1325.5 hectares, which will be

Table 3. The territories reserved for the next bequest of the Krasnokutsk community of Bohodukhiv district of Kharkiv region [24].

Name, category and type of territory	Estimated area, ha	Location	Characteristics
The hydrological reserve	6.9	Near Cherneshchyna village	The only forest lake of natural origin in the area. Habitat for rare species of aquatic flora
A complex natural monument	5.0	Near Horodne village	The beam is secured against collapse by brickwork terraces. A kind of acoustic effect is created
A complex natural monument	2.0	Parkhomivka forestry	Weymouth pine alley, 130 years old
General zoological reserve	33.0	Volodymyrivka forestry, 33	Habitat for rare species of animals: common burrowing owl, viviparous lizard, crested newt, Nikolsky's viper
Botanical reserve	20.0	Lavriki tract	Forested beam, a place of growth of medicinal plants rare for the region's flora
Botanical reserve	87.0	Near Moika and Kaplunivka villages	The upper reaches of the Khukhra River
Botanical reserve	80.0	Near Parkhomivka village	The upper reaches of the Kotelva River
Total	233.9		

Table 4. Areas to be protected as part of the ecological network of the Krasnokutsk community of Bohodukhiv district, Kharkiv region [24].

Name, category and type of territory	Estimated area, ha	Location	Characteristics
Slobozhansky National Nature Park	10000.0	Around Krasnokutsk town	The Merla River valley
Botanical reserve of local importance "Kapransky"	150.0	Near Kapranske village	A plot of meadows in the Merla River valley
Total	10150.0		

1.27 % (compared to the existing 1.05 %) of the total area of the community. The prospective territories of the nature reserve fund in the Krasnokutsk community of the Kharkiv region are shown in tables 3 and 4.

In modern conditions, the legislation defines the following stages of creation of the nature reserve fund territories (NRF):

1. Conducting a survey of the territory to identify objects requiring protection.
2. Preparation of a justification, including a description of the territory value (biological, historical, etc.).
3. Submission of the application to the responsible state authority (Ministry of Ecology in case of creation of territories of national importance, regional state administration in case of creation of territories of local importance).
4. Consideration and approval of the application by the responsible state body.
5. Approval of the application with the owners of land plots.
6. Development of the project for the formation of the territory.
7. Approval by the Cabinet of Ministers of Ukraine (the relevant commission of the regional council in case of creation of territories of local significance).
8. Signing of a Presidential Decree (for territories of national importance) or adoption of a decision by the regional council (in the case of territories of local importance).

As part of our study, we propose to supplement the stages of establishing nature reserve territories with the following recommendations.

At the stage of conducting a site survey to identify sites in need of protection, it is recommended to give preference to large and spatially coherent areas. It is also necessary to take into account the presence of several ecosystems in their natural state within the same site (e.g., river valley, steppe slopes, forest, etc.), which contributes to the increase of biodiversity in such a territory. The inclusion of reserved areas as objects of the nature reserve fund is an important step in expanding the nature reserve fund regime. Particular attention should be paid to the group of territories that were reserved in 1997 and still do not have the appropriate nature reserve status (table 5).

Table 5. The list of natural areas reserved for the creation of new or expansion of existing objects of the nature reserve fund (excerpt) [24].

Decision to reserve	Name of the territory/object offered to be created	Size, ha	Location
Decision of the Kharkiv Regional Council of the XIV session of the XXII convocation of 20.11.1997 “On reserving natural areas and objects for future conservation”	Ornithological reserve	328.0	Izium district (former Balakliya district) near Vilhuvatka village
	Soil reserve	50.0	Izyum district (former Balakliia district) near Petrivske village
	Paleontological reserve	96.6	Izium district (formerly Barvinkove) near the village of M.Garazhivka
	Botanical reserve	256.0	Izyum district (formerly Barvinkove) near Havrylivka village

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To expand existing protected areas, it is recommended to conduct a study of areas bordering or adjacent to existing protected areas. This research should be carried out by biological scientists, especially employees of nature reserves, national parks, universities, research institutes and other relevant institutions, in order to determine the possibilities and necessity of expanding these areas.

Working with the local population and land users is one of the most difficult and crucial stages in the process of creating protected areas [30, 31]. This is due to the fact that there is a low level of public awareness of conservation issues, which can lead to a lack of understanding of the need for conservation and even active resistance to these processes. Therefore, it is necessary to disseminate information (in the form of oral communication, through booklets, information leaflets, presentations, mass media, etc.) among the local population, landowners and land users about the benefits and limitations that will arise when creating a territory or object of the nature reserve fund in order to form a positive attitude towards this process.

4. Conclusions

The slowdown in the formation of new territories and objects of the nature reserve fund in Kharkiv region and Ukraine as a whole is a consequence of the current socio-economic situation. This problem needs to be addressed at the state level by amending the current legislation. In particular, it is necessary to simplify the procedures for creating new nature reserve sites, especially in terms of coordination with local governments and executive authorities. It is also important to introduce economic measures to encourage land users and landowners to create territories and objects of the nature reserve fund on their lands. This may include effective economic incentives and budgeting at all levels for the purchase of land plots for further preservation as protected areas.

Although the existing protected area indicator in Kharkiv region, defined as the ratio of the area of land in the nature reserve fund to the total area of the region, exceeds the average indicator for Ukraine by 1.4 %, it is significantly lower than in neighboring European countries and below the European average. Taking into account the natural, historical, physical and geographical features of the region, the optimal reserve rate for the region today is considered to be at least 10 %.

The solution of problematic issues is complicated by the lack of a clear strategy for the development of nature reserves and the lack of the management system coordination at the national and regional levels. The nature reserve fund of the Kharkiv region is distributed among different departmental structures, local governments and various business entities, including private enterprises. All of this makes it impossible to create a proper vertical management structure that would ensure effective management and control over the formation and maintenance of the nature reserve fund in the region.

Despite the long period of formation of the modern network of NRF in Kharkiv region, the functioning of protected areas faces legislative, institutional, organizational, and financial problems. To solve them, it is necessary to ensure the implementation of measures to ensure appropriate conditions for the implementation of a unified state policy in the field of reserve development in Ukraine, to create a scientifically based network of NRF objects and form an ecological network on its basis as a component of the Pan-European Ecological Network, to ensure the development and implementation of scientific research and monitoring of ecosystems, to create a system of balanced nature management, environmental education and recreational use of their resources on the basis of protected areas and NRF objects.

In order to intensify the processes aimed at achieving Goal 15 in Ukraine, it is necessary to intensify the work of local authorities to create new territories and objects of the nature reserve fund; to promote the transition to organic agriculture to preserve/improve soil fertility and biodiversity, reduce land and water pollution (artificial pesticides/herbicides, etc.); to take measures to harmonize policies related to the use of natural resources and their conservation; to ensure effective management of territories and objects of the nature reserve fund of local and national importance, including increasing the amount of financial resources allocated for the conservation of the nature reserve fund; to intensify work on the implementation of the National Action Plan to Combat Land Degradation and Desertification, the Strategy and the implementation of tasks on the neutral level of land degradation; to ensure improvement of economic mechanisms to stimulate land protection and restoration of soil fertility; to ensure the regulation of the transformation of the country's land structure (reduction of arable land, increase of forest cover, restoration of hayfields and pastures, etc.) in the process of decentralization of power and transfer of land from state ownership to the ownership of united territorial communities.

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Prerequisites for improving crop irrigation regimes on the basis of resource optimization

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Prerequisites for improving crop irrigation regimes on the basis of resource optimization

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Abstract. The article discusses the prerequisites for improving crop irrigation regimes on the basis of resource optimization. The current approaches to solving the problem of water shortages in irrigation are considered. The results of a machine experiment that reproduces research on the influence of the amount of water resource consumption on the yield of a cultivated crop in relation to the timing of irrigation are given. For the implementation of the machine experiment, a set of optimization, economic, mathematical and forecasting-simulation models was used, including a model of climatic conditions, a model of water regime and water regulation technologies, as well as a model of crop yields on reclaimed land for long-term forecasting. It has been experimentally shown that the impact of water resource shortages is weakened in the second half of the growing season, when crop yield losses are significantly lower than at the beginning of the growing season under similar conditions of water resource consumption. This fact provides prospects for the optimization of crop irrigation regimes as a component of resource optimization. The obtained results and the availability of a set of optimization, economic, mathematical and forecasting-simulation models create prerequisites for improving crop irrigation regimes on the basis of resource optimization.

1. Introduction

The existing global problems associated with climate change, food, water and energy crises pose a need for the world community, including Ukraine, to adapt to existing challenges and threats and to increase the efficiency of all spheres of economic activity, including agricultural production, in the face of modern changing conditions and requirements [1–4].

It is well known that melioration, and especially irrigation, is one of the most effective tools for reducing the negative effects of climate change on agricultural production, and irrigated land yields in 2–3 times higher yields compared to rainfed land. The predominant part of Ukraine's territory is located in the zone, which is characterized by an insufficient level of natural moisture. For the period from 1990 to 2010, the total area of arid and very arid zones, where sustainable agriculture is impossible without irrigation, increased by 8 million hectares. By that time, the restoration of hydrotechnical melioration, taking into account climate-oriented requirements, was already considered at the state level as an important condition for adapting agricultural production to the existing global food, water and energy crises, the threatening nature of which continues to increase in the context of climate change and creates new challenges. According to preliminary estimates, the deterioration of meliorative systems in Ukraine is 85%, and the area of actually irrigated land has been decreasing every year (2020 – 551 thousand hectares, 2021 – 525 thousand hectares, 2022 – 305 thousand hectares), and this is despite the fact that 2/3 of the territory of our country is at risk of agriculture [5]. Restoration of hydrotechnical melioration is a complex and expensive task, but it is necessary to ensure food security in Ukraine.

In order to achieve the goals of restoring hydrotechnical reclamation in 2019 the Cabinet of Ministers of Ukraine approved the Irrigation and Drainage Strategy in Ukraine until 2030 [6], and in 2020 adopted a plan for its implementation. In addition, to identify the existing needs for adaptation of economic sectors to climate change, in October 2021, the Cabinet of Ministers of Ukraine adopted the Strategy on Environmental Security and Climate Change Adaptation until 2030 [7], the first national document that creates a legislative framework for adaptation measures for systematic and long-term work on climate change adaptation.

Since the beginning of the full-scale war, the loss of Ukraine's sown areas caused by the temporary occupation and hostilities has amounted to more than 25% of the total amount, and the main part of these losses are highly productive irrigated lands. After Russia's terrorist attack on the Kakhovka Hydroelectric Power Plant, which led to a further reduction in sown areas, the problem of water shortages for irrigation, which is already relevant at both regional and global levels, reached a critical level [8].

In this regard, ensuring food security in the face of resource scarcity requires increasing the efficiency of irrigation, in particular by developing regime, technological and technical resource-saving measures, and means aimed at reducing the consumption of water and energy resources per unit of agricultural production, i.e. at obtaining the greatest possible effect from "one sown hectare" and "one drop of water".

There are several main approaches to implementing this idea: improving soil properties to increase its water-holding capacity; reducing evaporation from fields; and optimizing the amount of water for irrigation, including by improving irrigation techniques and crop irrigation regimes.

2. Materials and methods

Thus, modern conditions and requirements for conducting agricultural production make it necessary to change approaches to project decision-making in projects of construction, reconstruction and functioning, the purpose of which is to reduce the consumption of water and energy resources, which will ensure an increase in the economic and ecological efficiency of the functioning of irrigation systems in accordance with modern conditions and requirements and the efficiency of agricultural production on irrigated lands as a whole.

In recent years, the trend of targeted reduction of water consumption for irrigation has been gaining ground in the United States, when farmers deliberately reduce crop yields to reduce water consumption [9–11]. Similar practices are applied in China through the introduction of "deficit irrigation" [12–14]. In order to achieve the goal of reducing the values of resources used for agricultural production, the improvement of irrigation techniques and crop irrigation regimes should be based on research on the dependence of these values on the yield of cultivated crops, namely, that in the same year, due to the unequal distribution of the same amount of irrigation water, significantly different yields can be obtained. These provisions can be illustrated by the experimental data of Krafti and Kotov [15]. They studied the effect of different irrigation regimes on the corn yield in the case of a water shortage, when the irrigation rate was 2/3 of the required value.

To apply the entire irrigation rate, three waterings were required with the same watering rate, this option of irrigation was a control variant (№ 1). For the control variant with the full irrigation rate, irrigation was carried out during the periods of panicle ejection–flowering (I), stigma ejection (II) and milk ripeness (III). Different options with two waterings were studied, in which one of the three waterings was cancelled:

- № 2 – irrigation regime with cancellation of watering during period I;

- № 3 – irrigation regime with cancellation of watering during period II;
- № 4 – irrigation regime cancellation of watering during period III (figure 1).

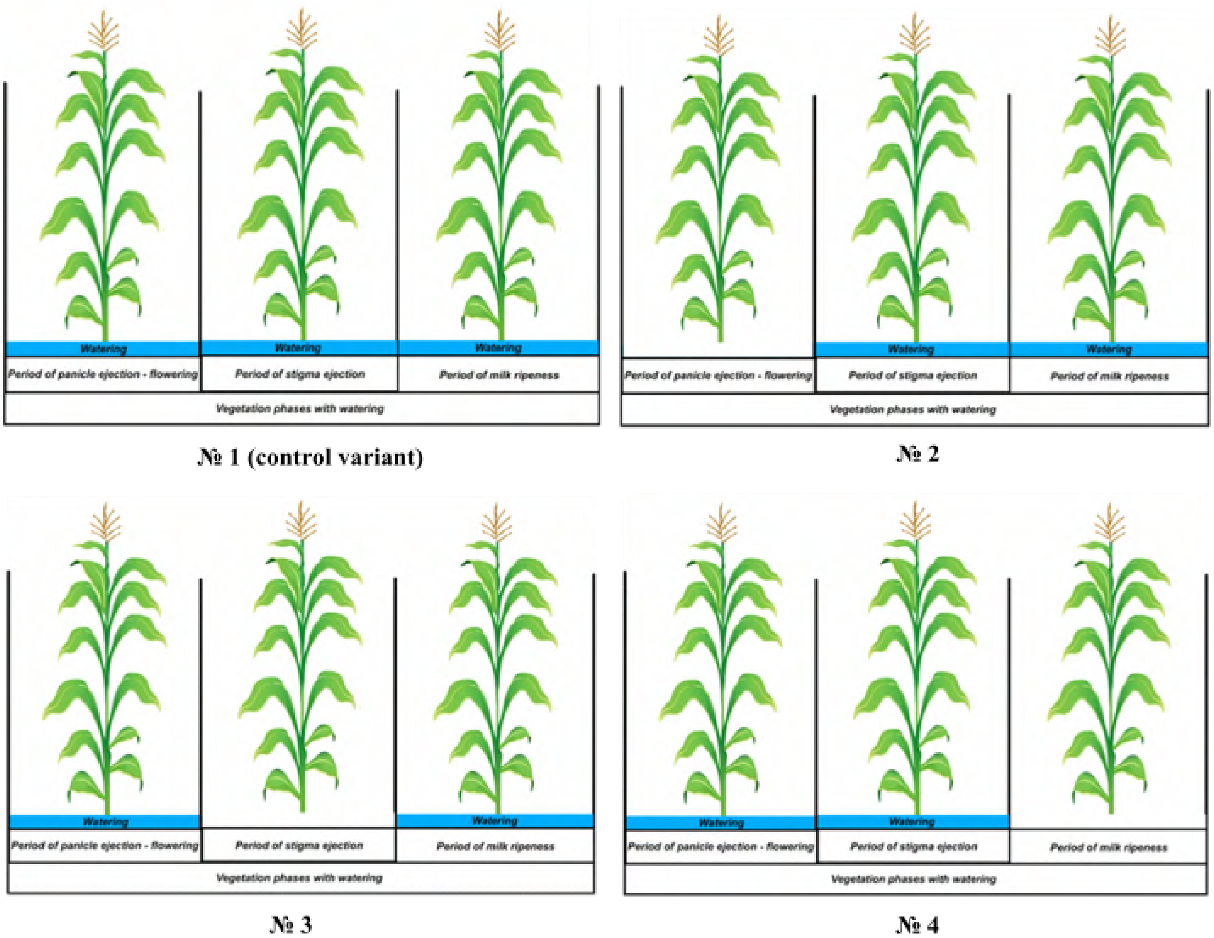

Figure 1. Scheme of options for research the impact of different irrigation regimes on corn yield [15]: № 1 (control variant) – variant with the full irrigation rate, irrigation was carried out during the periods of panicle ejection–flowering (I), stigma ejection (II) and milk ripeness (III); № 2 – irrigation regime with cancellation of watering during period I; № 3 – irrigation regime with cancellation of watering during period II; № 4 – irrigation regime cancellation of watering during period III.

Table 1 summarizes the results of research the impact of different irrigation regimes on corn yield. It shows the ratio of actual yield obtained according to the research options with cancellation of waterings to the yield according to control variant with three waterings. The obtained results are quite indicative: when the first watering is canceled, the ratio of actual yield to the control variant is 0.67; when the second watering is cancelled – 0.78; when the third watering is cancelled – 0.93.

Despite the fact that this research was carried out in the 70s of the last century, this area has not yet gained a sufficient level of study and development, due to the insufficient computer capabilities at that time and the lack of mathematical models capable of describing and reproducing the complex dynamic processes of crop yield formation and the effects of heterogeneous factors of influence. A similar approach was partially implemented in the studies

Table 1. Estimation the impact of different irrigation regimes on corn yield for the case of water shortage [15].

Research options	Vegetation phases with watering			Ratio of actual irrigation rate to control variant	Ratio of actual yield to control variant
	period of panicle ejection–flowering	period of stigma ejection	period of milk ripeness		
№ 1 (control variant)	I	II	III	1.0	1.0
№ 2	–	II	III	0.75	0.67
№ 3	I	–	III	0.75	0.78
№ 4	I	II	–	0.75	0.93

presented in [16, 17]. The results showed that meeting the crop water requirement during the reproductive stage is more important than during the vegetative stage of growing season.

Based on the software complex (computer program) [18] developed in the research laboratory "Optimization and automation of control in water engineering and water technologies" at the Department of Water Engineering and Water Technologies of the National University of Water and Environmental Engineering (Rivne, Ukraine), a machine experiment that actually reproduces the main idea of research described in [15] was conducted. The software complex used for **the machine experiment is based on a set of forecasting-simulation, economic-mathematical and optimisation methods and models**, including a model of climatic conditions, a model of water regime and water regulation technologies, as well as a model of crop yields on reclaimed land for long-term forecasting, the application of which is regulated by the relevant industry regulations of the State Agency of Water Resources of Ukraine.

Thus, the **aim of the research** is to assess the impact of reducing water and energy resources during irrigation on the productivity of cultivated crops in the conditions of increasing shortage of irrigation water due to climate change. The **object of research** is the process of the impact of cancelling crops watering at different periods of the growing season on their productivity.

3. Results and discussions

The purpose of the conducted machine experiment is a predictive-simulation reproducing of the idea of the experiment by Krafti and Kotov [15] for our conditions on the example of growing perennial grasses as a moisture-loving crop of crop rotation in the Kherson region. Using for machine experiment software complex [18] allows to further implement a predictive assessment of the impact of reducing water and energy resources during irrigation on the productivity of cultivated crops in the conditions of increasing shortage of irrigation water due to climate change, as an extremely serious problem of our time in irrigated agriculture. As the main options of research, a set of irrigation regimes that differ in the cancellation of waterings in different periods of the crop's vegetation (watering rate 400 $m^3 \cdot ha^{-1}$) are considered:

- № 1 (control variant) – irrigation regime with six waterings, irrigation rate 2400 $m^3 \cdot ha^{-1}$;
- № 2 – irrigation regime with cancellation of the first watering, irrigation rate 2000 $m^3 \cdot ha^{-1}$;
- № 3 – irrigation regime with cancellation of the second watering, irrigation rate 2000 $m^3 \cdot ha^{-1}$;

Table 2. Evaluation of technological efficiency of perennial grasses irrigation regimes in the conditions of Kherson region.

Research options	Vegetation period, decades													Irrigation rate, $m^3 \cdot ha^{-1}$	Actual yield, $kg \cdot ha^{-1}$	Ratio of actual yield to control variant
	12	13	14	15	16	17	18	19	20	21	22	23	24			
№ 1 (control variant)	0	400	0	400	0	400	0	400	0	400	0	400	0	2400	4060	1.0
№ 2	0	-	0	400	0	400	0	400	0	400	0	400	0	2000	3290	0.81
№ 3	0	400	0	-	0	400	0	400	0	400	0	400	0	2000	3560	0.88
№ 4	0	400	0	400	0	-	0	400	0	400	0	400	0	2000	3750	0.92
№ 5	0	400	0	400	0	400	0	-	0	400	0	400	0	2000	3780	0.93
№ 6	0	400	0	400	0	400	0	400	0	-	0	400	0	2000	3790	0.93
№ 7	0	400	0	400	0	400	0	400	0	400	0	-	0	2000	3810	0.94

- № 4 – irrigation regime with cancellation of the third watering, irrigation rate 2000 $m^3 \cdot ha^{-1}$;
- № 5 – irrigation regime with cancellation of the fourth watering, irrigation rate 2000 $m^3 \cdot ha^{-1}$;
- № 6 – irrigation regime with cancellation of the fifth watering, irrigation rate 2000 $m^3 \cdot ha^{-1}$;
- № 7 – irrigation regime with cancellation of the sixth watering, irrigation rate 2000 $m^3 \cdot ha^{-1}$.

The summary results of the implemented machine experiment according to the above research

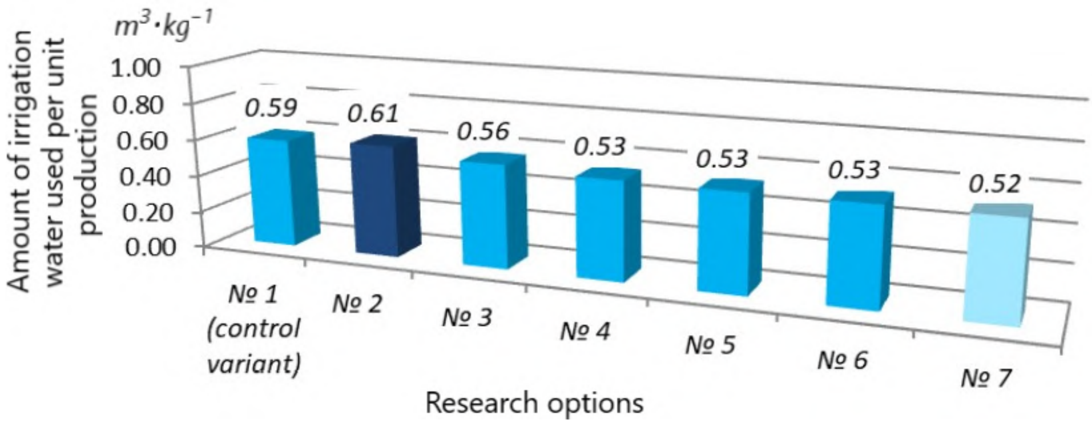

Figure 2. Amount of irrigation water used per unit of plant production of the cultivated crop, $m^3 \cdot kg^{-1}$: № 1 (control variant) – irrigation regime with six watering; № 2 – irrigation regime with cancellation of the first watering; № 3 – irrigation regime with cancellation of the second watering; № 4 – irrigation regime with cancellation of the third watering; № 5 – irrigation regime with cancellation of the fourth watering; № 6 – irrigation regime with cancellation of the fifth watering; № 7 – irrigation regime with cancellation of the sixth watering.

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options are presented in table 2.

These data (table 2) clearly show the nature of the impact of water resource consumption on crop yield in relation to the timing of watering. The impact of water shortages is particularly pronounced in the second half of the growing season, when crop yield losses are significantly lower than at the beginning of the growing season under similar conditions.

According to the obtained results for the research options, an indicator of the productivity of irrigation water use was defined as the amount of irrigation water consumed per unit of plant production (figure 2).

The obtained results and the availability of a set of optimization, economic, mathematical and forecasting-simulation models create prerequisites for optimization of crop irrigation regimes as a component of resource optimization, the basic principles and principles of implementation of which are considered in [19], and optimization of water and energy use of resources in general as a prerequisite for increasing the efficiency of irrigation and agricultural production in relation to modern changing conditions and requirements.

4. Conclusions

1. Modern conditions and requirements for conducting agricultural production make it necessary to change approaches to project decision-making in projects of construction, reconstruction and functioning, the purpose of which is to reduce the consumption of water and energy resources.
2. In order to achieve the goal of reducing the values of resources used for agricultural production, the improvement of irrigation techniques and crop irrigation regimes should be based on research on the dependence of these values on the yield of cultivated crops, namely, that in the same year, due to the unequal distribution of the same amount of irrigation water, significantly different yields can be obtained.
3. In order to research the influence of water consumption on the yield of a cultivated crop in relation to the timing of irrigation, a machine experiment was conducted using a set of optimization, economic, mathematical and forecasting-simulation models, including a model of climatic conditions, a model of water regime and water regulation technologies, as well as a model of crop yields on reclaimed land for long-term forecasting.
4. The machine experiment is based on the experimental data of Bulgarian researchers Krafti G. and Kotov L. concerning the effect of different irrigation regimes on the corn yield in the case of water shortage. Despite the fact that this research was carried out in the 70s of the last century, this area has not yet gained a sufficient level of study and development, due to the insufficient computer capabilities at that time and the lack of mathematical models capable of describing and reproducing the complex dynamic processes of crop yield formation and the effects of heterogeneous factors of influence.
5. The results of the machine experiment proved that the impact of water resource shortages is weakened in the second half of the growing season, when crop yield losses are significantly lower than at the beginning of the growing season under similar conditions. This fact provides prospects for optimization crop irrigation regimes as a component of resource optimization.
6. The obtained results and the availability of a set of optimization, economic, mathematical and forecasting-simulation models create prerequisites for improving crop irrigation regimes on the basis of resource optimization, which will ensure an increase in the economic and ecological efficiency of the functioning of irrigation systems in accordance with modern conditions and requirements and the efficiency of agricultural production on irrigated lands as a whole.

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Structural and functional content of xerophytic plants of *Elytrigia repens L.* genus

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Structural and functional content of xerophytic plants of *Elytrigia repens L.* genus

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Abstract. In the modern conditions of the ecological crisis, the study of adaptive changes in xerophyte plants, which form natural and cultural phytocenoses, has important theoretical and practical significance. Steppe phytocenoses of the Zaporizhia region, especially the Melitopol city and the Melitopol district, are represented by xerophytic associations. The research aim was to find out the histological and physiological rearrangements of the organs of the genus *Elytrigia L.* to determine adaptation features at the tissue level to water and temperature stresses. The subject of the study was the study of the structural and functional features of plant organs of the genus *Elytrigia repens L.* during adaptation to environmental factors (on the example of the Zaporizhzhia region, in particular the Melitopol city). The theoretical and methodological basis of the work was the synergistic use of a systemic approach, which led to a transparent approach to the choice of research methods, in particular: general scientific (analysis, synthesis, systematization, generalization of literary sources); general biological (experimental method, quantitative-anatomical, physiological and system-structural analysis, methods of mathematical statistics. It was established that the adaptation of xerophytes of the genus *Elytrígia L.* to arid habitats is characterized by structural and functional rearrangements of vegetative organs, in particular, the presence of unicellular trichomes, which ensures a decrease in transpiration, an increase in the share of storage tissues in the leaf and conductive and mechanical elements in the stem, as well as a decrease in intensity photosynthesis under drought conditions. As a result of finding out the functional disturbances in the leaf under the influence of drought, in particular the intensity of photosynthesis and the specificity of the pigment composition of the experimental plant, it was proved that the experimental plants under normal conditions have a parabolic curve of photosynthesis, and under the influence of atmospheric drought these indicators have a hyperbolic shape, and the analysis of the results of daily of the dynamics of photosynthesis established that the most intense photosynthesis occurs in plants under normal conditions, and under the influence of drought in plants there is a decrease and inhibition of the process of photosynthesis.

1. Introduction

The climate aridization and the significant expansion of arid areas due to the global increase in temperature with a simultaneous decrease in precipitation and a decrease in soil moisture attracts the attention of many researchers. In such conditions, the study of adaptive changes in xerophyte plants, which form natural and cultural phytocenoses, has important theoretical and practical significance. The results of quantitative and anatomical researches can be used in systematics, histology and ecology of plants [1–4], as they allow establishing the main adaptive features characteristic of this particular group, which is important for establishing the paths of evolution of the plant world as a whole.

The Melitopol city is a multi-sector industrial center located on the right bank of the once navigable Molochnaya River, but currently, unfortunately, it is temporarily occupied. In 2021, the total area of green areas was 2.2 thousand hectares. About 70% of the city's territory is located on the watershed with average heights of 34-40 m, the rest – on the steep slope of the Molochna River valley. The territory of the city and district is located mainly within the Black Sea Lowland. Its surface is a flat lowland plain, descending from north to south, where it ends with a steep (up to 20 m high) ledge on the shore of the Azov Sea. In the northeast, spurs of the Azov Highlands with absolute height marks from 150 to 250 and more meters above sea level extend into the border [5].

The main feature of the city's climatic conditions is hot summers, moderately cold winters and insufficient humidity. The average monthly air temperature in July is +29°C. The duration of the summer period, when the average daily temperature exceeds +15°C, is 126-138 days. The average monthly temperature in January is -4°C. The absolute minimum reaches -30°C. The average annual amount of precipitation is 400 mm and varies from 350 to 450 mm [6–11].

The soil cover on the territory of the watershed part of the city is represented by sandy and sandy-medium loamy soils of the chernozem type, which are formed on an ancient terrace, on ancient alluvial deposits.

The characteristic xerophytes of the specified region are representatives of the specy *Elytrígia repens L.* – perennial herbaceous plants from the genus *Elytrígia L.*, which belongs to the Poaceae family and includes about 100 species.*Elytrígia L.* is one of the most common and harmful weeds in crops and plantations of cultivated plants, forest areas, and forest clearings. But at the same time *Elytrígia repens L.* acts as a useful medicinal, fodder and food plant. As a medicine, wheatgrass helps to get rid of many diseases not only for humans, but also for animals. On the territory of Ukraine, the most common *Elytrigia repens L.* The name of this plant speaks for itself – this herbaceous plant has a long creeping rhizome, which starts flowering at the end of April and until July, the fruits – grains ripen in July – September. *Elytrigia repens L.* is a medicinal plant, drugs from which are used for metabolic disorders, as a diuretic, diaphoretic, pain reliever, expectorant, and laxative that regulates salt metabolism. The unique ability of *Elytrigia repens L.* is to remove strontium-90 from the body thanks to tannin, which is contained in a sufficient amount; when with increased outflow of water from the body, slags are released, which is manifested primarily in the reduction of skin rashes, fatigue and the state of brokenness are relieved. At the same time, all components work together, both vitamins and minerals [12–16]. *Elytrigia repens L.* as a food plant; it helped people more than once in the most difficult times. *Elytrigia repens L.* rhizome is used for food. It is ground, flour is obtained, which is not inferior to wheat in terms of nutrition, and bread, cakes, gingerbread, and other flour products are baked [16–18]. Therefore, the study of structural and physiological features of representatives of the genus *Elytrigia repens L.* is becoming more and more relevant.

In this regard, the research aim was to find out the histological and functional rearrangements of the organs of the genus *Elytrigia L.* to determine adaptation features at the tissue level under the effects of water and temperature stresses.

The research subject of the study was the study of the structural and physiological features of *Elytrigia repens L.* plant organs during adaptation to environmental factors (on the example of the Zaporizhzhia region, in particular the Melitopol city).

The research object was *Elytrigia repens L.* plants of arid habitats of the Zaporizhzhia region. Systematic position is division Magnoliophyta; class Monocotyledons (*Liliopsida*); order *Poales*; family *Poaceae*; genus *Elytrigia*; specy *Elytrigia repens (L.) Gould*.

Botanical characteristics. Elytrigia repens (L.) Gould) – a perennial plant from the genus

Elytrigia L.; medicinal, fodder and food plant, which grows in areas with steppe vegetation, is found in the steppe regions of Ukraine. A herbaceous plant with a long creeping rhizome, which penetrates the soil in the first year of life by 75 cm, the second – by 195 cm, the third – by 250 cm. The main mass of rhizomes with buds that give rise to a new plant is located no deeper than 20 cm, and on compacted soils up to 8-10 cm. The fruit is a grain. The color is grayish-green. Size – length 6-10 mm, width – 1.25-1.75 cm, thickness 1-1.25 mm. The weight of 1000 grains is 3-4 g. It comes from grains and shoots of underground buds in March-May. It blooms in June-July, fruits in July-August. The stems are erect or ascending, cylindrical, green, with thickened nodes and hollow internodes. Leaves (3-10 mm wide) alternate, sessile, linear, flat, and smooth from below, rough from above, often with thin hairs along the veins. The vagina is bare, smooth, the tongue is short. Inflorescence is an upright complex spike (up to 15 cm long). Spikelets (10-18 mm long) are multi-flowered, lanceolate, sitting on the protrusions of the spike axis. Spike scales (6-12 mm long) are lanceolate, sharp with five to seven veins, smooth or rough. The lower flower scale (7-10 mm long) is lanceolate, glabrous, blunt at the top, pointed or with a short spine. Stamen is three, pistil – one and ovary upper with two pinnate receptacles.

Biological features: maximum fertility – 19 thousand grains. The depth of germination in the freshly reached state – they germinate from a depth of no more than 7-10 cm. Segments of rhizomes 5-15 cm long form shoots from a depth of up to 25 cm. Viability in the soil – more than 5 years.

Environmental requirements: germination temperature – minimum: +2..+4°C and optimal: +20...+30°C. Terrestrial organs are damaged at a temperature of -10...-12°C [19, 20]. *Elytrigia repens L.* grows on wastelands, deposits, forest clearings, along forest edges, near roads, in meadows, arable land, and gardens. It is difficult to eradicate it due to its long, creeping and knotty rhizome, and if you leave pieces of the roots of this plant in the ground, they do not die and give new shoots. But wheatgrass rhizomes dry out quickly outside the soil. This plant also exists well in fields and pastures, including on saline and limestone soils, near roads, houses, throughout the territory of Ukraine [5, 21].

Practical use: in traditional medicine, rhizomes are used for diseases of the respiratory tract and kidneys, as a blood purifier, for nocturnal urinary incontinence, for partial loss of vision, for pulmonary tuberculosis, jaundice, menstrual cycle disorders, rheumatism, for venereal diseases, dropsy, and urinary stones. and bile ducts, rickets, boils, inflammation of the bladder and hemorrhoids; in homeopathy; in animal husbandry – a valuable fodder plant: meadow and fallow hay, mowed before flowering, is characterized by high nutritional properties. On pastures, wheatgrass is eaten by all types of livestock, it is considered a milk-producing agent for cows [7–10]. In the flowering phase, it contains 9% protein, 2.7% fat, 31% fiber, and 47% nitrogen-free extractives. Hay yield on fallow ranges from 6 to 15 t/ha, on flooded meadows – 20-60 t/ha [22, 23]. *Elytrigia repens L.* rhizomes contain polysaccharide tricytin, gum, mucilage, malic and other acids, essential oil, carotene, vitamin C, starch. Ground rhizomes are used to make flour, which can be used to prepare drinks, including beer.

2. Methodology

The theoretical and methodological basis of the work was the synergistic use of a systemic approach, which led to a transparent approach to the choice of research methods, in particular: general scientific (analysis, synthesis, systematization, generalization of literary sources); general biological (experimental method, quantitative-anatomical (using the methods of Pausheva, Baranova, Zakharevich), physiological (Kazakov) [24] and system-structural analysis [18, 25]; methods of mathematical statistics. Statistical analysis of the obtained data was carried out using the general data processing software package Statistica version 10.0. Arithmetic mean (M) and standard error of the mean (SEM) were calculated to compare the samples. A difference of p $\leq$0.05 was considered statistically significant for all indicators. Quantitative and anatomical studies were carried out on material from normally developed plants, collected in the city of Melitopol, Zaporizhzhia region (repetition 3 times).

3. Results

Steppe phytocenoses of Zaporizhzhya region, especially Melitopol and Melitopol district, are represented by xerophytic associations. These are mostly herbaceous plants, which, depending on the degree of dryness of the area, are divided into main groups: succulents, euxerophytes, hemixerophytes, poikiloxerophytes, and ephemera. The main indicators of adaptation to the conditions of minimum water supply are as follows:

1) a reduced, and sometimes completely reduced leaf blade or leaves fall during the greatest drought;
2) the leaves and stem are covered with an epidermis with a well-developed cuticle, leathery, often with a hairy covering or a wax coating;
3) the cells of the epidermis and mesophyll are small in size, and in connection with this, there is a greater number of them per unit surface, including a greater number of stomata;
4) significant development of conductive and mechanical elements, and in connection with this, a large density of veins on the leaves;
5) high concentration of cell juice.

The epidermis study of the *Elytrígia répens L.* leaf according to the Zacharevich method in terms of outlines, projection, and dimensions allowed us to identify the following types of basic cells: type I – cell outlines are tortuous, the projection is rectangular-elongated, the corners are rounded, obtuse, the number per unit area is 125-130 units/cm^2, the short axis is 21.25 μm, the long axis is 38.75 μm, S cell is 823.44 μm^2; II type – outlines of cells are rectilinear and strongly sinuous, the projection is flattened, the corners are sharp, rounded, the number per unit area is 135-140 pcs/cm^2, the short axis is 18.75 μm, the long axis is 41.25 μm, S cells – 773.44 μm^2; type III – cell contours are sharply tortuous, the cell projection is square, the number per unit area is 115-120 pcs/cm^2, the short axis is 21.25 μm, the long axis is 45 μm, cells plane is equal to 956.25 μm^2.

Stomatal complexes on the leaf adaxial side are absent, but on the abaxial side, it is clearly expressed, of the anomocytic type, their number per unit area is 245-250 pcs/mm^2. The height of the cells of the upper epidermis is 41-45 microns. On the upper epidermis, the size of the main cells in comparison with the lower side is 2-3 μm larger, their number decreases: type I – 115-120 pcs/cm^2; II type – 120-125 pcs/cm^2; III type – 110-115 pcs/mm^2.

Endo-structural analysis of the structure of the *Elytrígia répens L.* leaf proved that the leaf is covered with simple, unicellular trichomes. The leaf mesophyll has an isolateral structure and consists of 5-7 layers of palisade-type cells. The length of the cells exceeds the width by 2-2.5 times. The cells of the palisade tissue are closely adjacent to each other; the intercellular spaces are almost invisible. The conducting bundles are collateral, located in the middle layers of the leaf plate. The bundles are surrounded by small, thin-walled parenchymal cells that make up the covering of the conducting bundle. Visual ratio of *Elytrígia répens L.* leaf tissues is shown in figure 1.

Thus, the structural analysis of the primary covering tissue and the internal structure of the *Elytrígia répens L.* leaf showed that the leaf is covered with simple, unicellular hairs; the epidermis is formed by the main cells of three types, which differ from each other in terms of outline, projection, angles, dimensions and quantity per unit surface, whereby the upper epidermis of the leaf makes up 4.53% of the total thickness, the lower epidermis – 3.83%; stomatal complexes of the anomocytic type, their number is 245-250 pcs/cm^2, the location is only on the

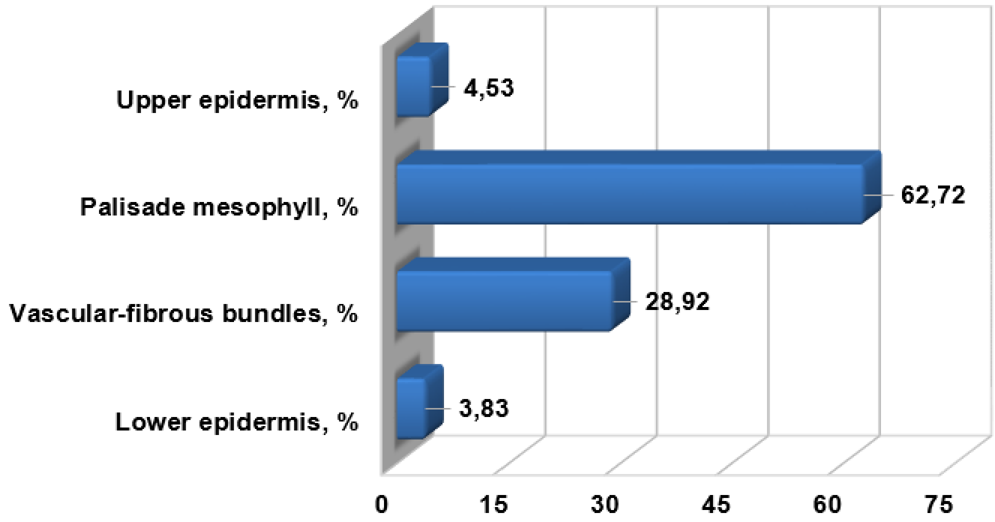

Figure 1. Histological and structural characteristics of *Elytrígia répens L.* leaf (p $\leq$0.05).

lower side of the leaf, i.e. the leaf is hypostomatic. The mesophyll has an isolateral structure, the conductive bundles are collateral, located in the middle layers of the leaf plate, the mesophyll is 62.72% of the total thickness, and the conductive bundle is 28.92%.

The study of the *Elytrígia répens L.* stem in three parts: under the inflorescence, in the middle part and the bottom showed that it has a mixed type of structure and consists of the primary bark, which includes the epidermis, and then two or three layers of angular collenchyma and parenchyma of the bark are placed. It is represented by elongated cells with thin membranes. Cambium is presented in the form of one or two layers of cells, located between the bark and the wood. The xylem in its composition has tracheae of three orders, which are placed in rows, between them are libriform cells. Large vessels are located closer to the phloem. The core consists of multi-angular cells with thin membranes.

The quantitative characteristics analysis of the *Elytrígia répens L.* stem shows that the primary bark occupies from 24 to 27% of the total thickness of the organ in the stem, the bark has the smallest value under the inflorescence, but its size gradually increases due to the growth of the parenchyma of the bark. The cambium layer occupies about 0.14% and throughout the stem, its dimensions almost do not change. The size of the xylem increases when moving from the upper to the lower part of the stem, its part accounts for 17-22%. The core occupies 57% in the upper part, 55% in the middle and 49% in the lower part of the stem (figure 2).

So, our research showed that the *Elytrígia répens L.* stem has a mixed type of structure, consisting of the primary cortex, which is 26.3%, interbundle and bundle cambium – 0.12%, xylem represented by tracheae of three orders – 19.31% and the core, which occupies 54.28% of the total thickness of the stem (figure 3).

Violation of the physiological functions of plants in drought conditions is the first reaction-response of the body to water deficit. Changes in the microstructure appear, as a rule, as a result of functional disorders. According to the degree of sensitivity to phytotoxicants, individual functions of plants can be arranged in the following order in descending order: photosynthesis, respiration, biosynthesis of secondary substances, transpiration, growth and development. The specified sequence is conditional, since the initiated changes of one function entail disturbances in others [13–16]. Carbohydrates are a product of photosynthetic energy storage, serve as a substrate and source of energy for further biosynthetic processes. Violations of the photosynthetic and respiratory functions of plants invariably affect the quantitative content and relatively different forms of carbohydrates.

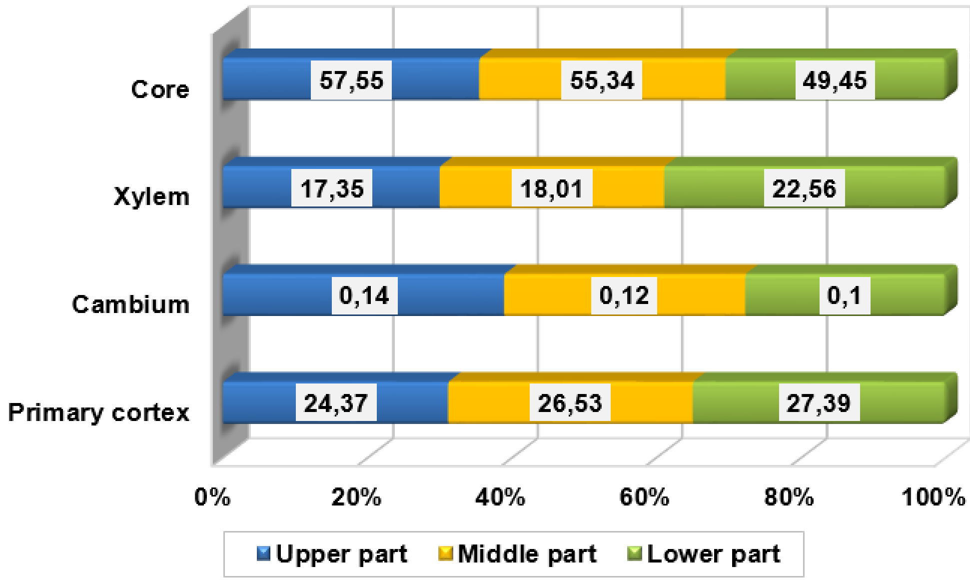

Figure 2. Quantitative and histological characteristics of the *Elytrígia répens L.* stem (in three parts) (p ≤0.05).

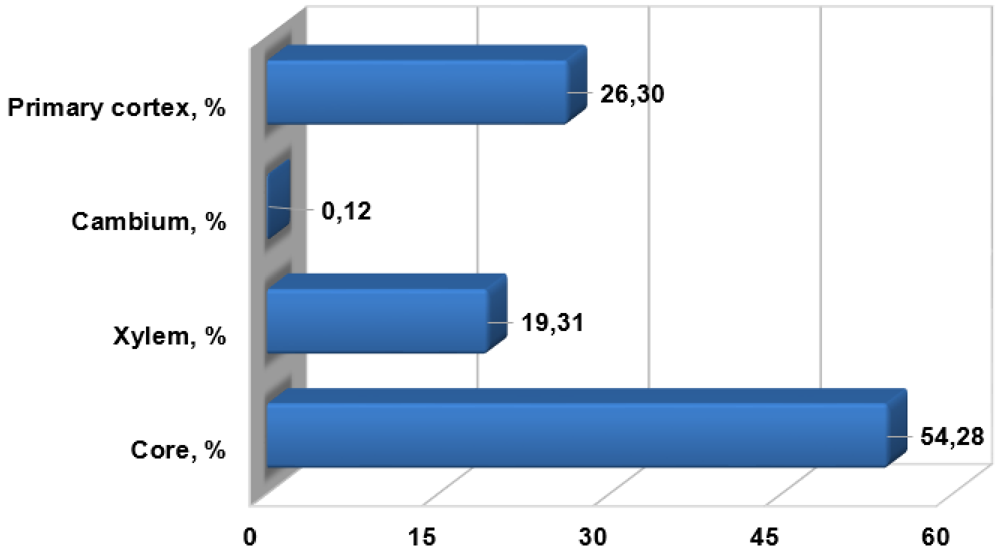

Figure 3. Tissues generalized ratio of a mixed type of *Elytrígia répens L.* stem (p ≤0.05).

Our studies have shown that the daily dynamics of photosynthesis in the studied plants under normal conditions of moisture has a parabola-like shape: with the lowest indicators at 12-1 p.m. of the day, the biggest ones – at 5-6 p.m. days the difference between them is 25% (figure 4).

The photosynthesis daily dynamics of experimental plants under the influence of drought has a hyperbolic shape, with the highest indicators at 9-10 a.m. days, which gradually decrease to 5-6 p.m. The difference between them is 66% (figure 5).

So, the experimental data showed that mainly experimental plants under normal conditions have a parabolic curve of photosynthesis, and under the influence of atmospheric drought these indicators have a hyperbolic shape. Thus, the analysis of the results of the photosynthesis daily dynamics established that the most intensive photosynthesis occurs in plants under normal

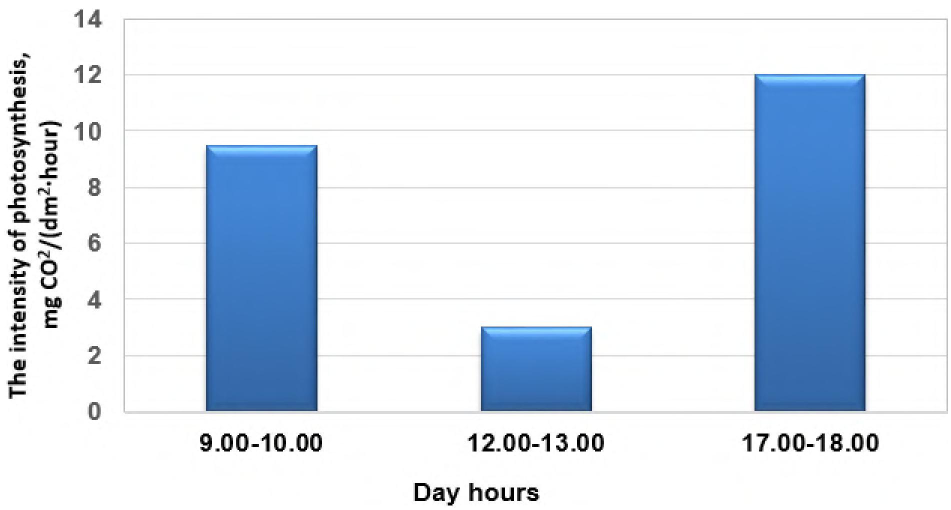

Figure 4. Photosynthesis daily dynamics of plant *Elytrígia répens L.* under normal conditions ($p \leq 0.05$).

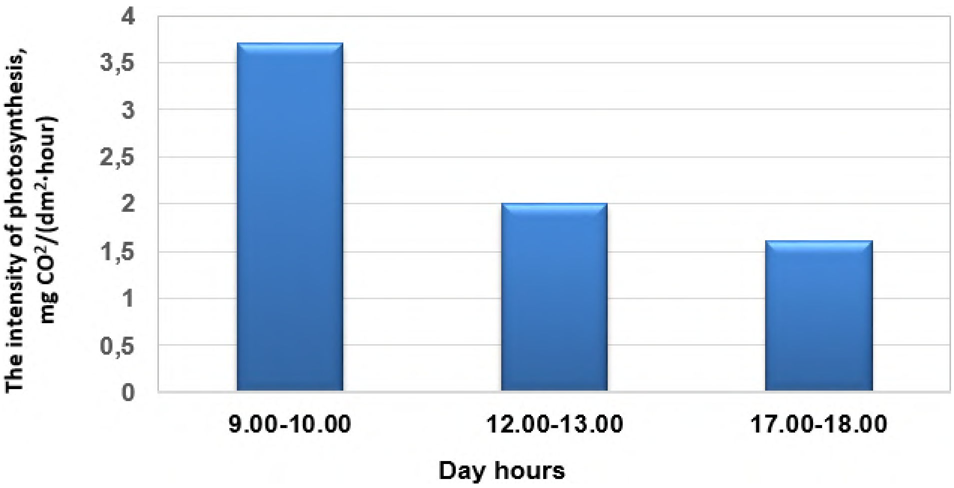

Figure 5. Photosynthesis daily dynamics of experimental plants under the droughts influence ($p \leq 0.05$).

conditions, and under the influence of drought, a decrease in the photosynthesis process is observed in plants.

4. Conclusions

The reseaches of the structural and functional characteristics of *Elytrígia repens L* plants allows us to draw the following conclusions:

1) the study of morpho-anatomical indicators of plant Elytrígia répens L. organs showed that:
   - the *Elytrígia répens L.* leaf is covered with simple, unicellular hairs; the epidermis is formed by the main cells of three types, which differ from each other in outline, projection, angles, sizes and quantity per surface unit, with the upper epidermis of the leaf accounting for 4.53% of the total thickness, the lower epidermis for 3.83%; stomatal complexes of the anomocytic type, their number is 245-250 pcs/cm^2, they are located

only on the lower side of the leaf, i.e. the leaf is hypostomatic, the mesophyll has an isolateral structure, the conducting bundles are collateral, located in the middle layers of the leaf plate, the mesophyll is 62.72% of the total thickness, and the leading beam – 28.92%;

- the *Elytrígia répens L.* stem has a mixed type of structure, consisting of primary bark, which is 26.3%, between bundle and bundle cambium – 0.12%, xylem, represented by tracheae of three orders – 19.31%, and core, which occupies 54.28% of the total thickness of the stem;

2) elucidation of functional disorders in the leaf under the influence of drought, in particular the intensity of photosynthesis and the specificity of the pigment composition of the experimental plant proved that mainly experimental plants under normal conditions have a parabolic curve of photosynthesis, and under the influence of atmospheric drought these indicators have a hyperbolic form, and the analysis of the results of daily dynamics of photosynthesis established that the most intense photosynthesis occurs in plants under normal conditions, and under the influence of drought, a decrease in the photosynthesis process is observed in plants.

In general, we proved that the adaptation of xerophytes of the genus *Elytrígia L.* to arid habitats is characterized by the presence of unicellular trichomes, which ensures a decrease in transpiration, an increase in the share of storage tissues in the leaf and conducting and mechanical elements in the stem, as well as a decrease in the intensity of photosynthesis under drought conditions.The obtained results form a holistic view of the structural and physiological content of the vegetative organs of xerophytic weed plants, which contributes to the development of effective means of control and effective use in the interests of humans.

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Bioenergetic efficiency of growing miscanthus with sewage sediment

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Abstract. Cultivation of energy crops becomes relevant in areas with a high climatic potential for biomass accumulation. Many studies have established the effectiveness of applying sewage sludge on various types of soil, including under miscanthus and increasing biomass collection of various doses of its application. Field experiments were conducted in the West of our country, namely in the territory of the Ivano-Frankivsk Region, Tsenzhiv Yamnytska united territorial community. Application of growing fertilizers based on compost ($SS-40$ t/ha $+N_{10}P_{14}K_{58}$ and Compost (SS + $straw(3:1))-20$ t/ha $+N_{50}P_{16}K_{67}$) ensures the highest yield of dry biomass of miscanthus (29.8 *and* 27.3 t/ha), as well as the output of gross energy ($547-578$ GJ/ha), which led to an increase in the energy efficiency coefficient from 3.3 to 4.1. Such a relationship describes the regression equation of the linear regression with the coefficients of determination ($R^2 = 0.73$).

1. Introduction

Cultivation of energy crops is gaining relevance in areas with high climatic potential for biomass accumulation [1, 2]. In Ukraine, in order to diversify the supply of energy and increase the share of renewable sources in the state's energy balance, the cultivation of bioenergy crops, in particular miscanthus, is becoming widespread, which is characterized by a number of positive characteristics, one of which is a high level of accumulation of dry mass, which can easily be processed into first and second generation fuel [3, 4].

As a rule, low-productive degraded areas marked by a low level of effective fertility are set aside for planting energy crops, including miscanthus [5–7]. Therefore, it is important to establish effective methods of growing miscanthus with the introduction of various fertilizers. One of the effective sources of replenishment of organic matter in the soil and elements of mineral nutrition is the sewage sludge of the municipal economy, which is characterized by an increased content of nutrients [8, 9].

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Many studies have established the effectiveness of applying sewage sludge on various types of soil, including under miscanthus, and increasing the biomass collection of various doses of its application [10–12]. However, the issue of bioenergetics of using sewage sludge for miscanthus is insufficiently studied, which led to the implementation of our research.

2. Literature analysis and problem statement

Miscanthus, also known as "silver cane", is an annual herb that is used as an energy crop. It has gained popularity due to its high productivity and the possibility of use as a renewable source of bioenergy. Miscanthus can achieve high yields per hectare, making it an efficient choice for bioenergy production [4, 6, 10].

This plant is characterized by high resistance to various climatic conditions and requires little care, including minimal soil requirements.

Miscanthus has a positive impact on the environment, able to absorb carbon dioxide during its growth, which reduces greenhouse gas emissions.

In addition to the production of bioenergy, miscanthus can be used for the production of paper, bioplastics, and even as a material for construction [9, 13].

With low growing and maintenance costs, miscanthus is an economically viable crop for farmers. Miscanthus can help improve soil structure and prevent erosion.

One planting can produce crops for 15-20 years without the need for annual transplants. Miscanthus can be converted into various forms of energy, including bioethanol, biodiesel and solid fuels [7, 12].

Overall, miscanthus is considered a promising crop for bioenergy production, which can help reduce fossil fuel dependence and promote sustainable development.

The energy efficiency of miscanthus as an energy crop is quite high, making it an attractive choice for bioenergy production.

Miscanthus is characterized by high productivity, the ability to produce significant amounts of biomass per unit area, exceeding many other crops, requiring relatively little energy to grow, harvest and process compared to the energy that can be obtained from its biomass. This makes it energy efficient. The energy crop has low agronomic requirements, in particular the minimal need for fertilizers and pesticides after the establishment of the field, which reduces energy costs for its maintenance. In our research, we used sewage sludge. Miscanthus can be processed into various fuels, including solid biofuels (pellets, briquettes), bioethanol and other biofuel products. In addition to bioenergy production, miscanthus can be used to create bioproducts, which further increases its energy efficiency [10, 11, 14].

Overall, miscanthus is considered one of the most energy-efficient bioenergy crops due to its high yield, low cultivation and maintenance costs, and ability to convert into various forms of energy.

Applying sewage sludge to miscanthus can be agronomically and ecologically beneficial, but it also requires careful consideration and control. Sewage sludge, sometimes called biosludge, can be rich in organic matter and nutrients that are beneficial to plant growth, including miscanthus. However, there are certain aspects to consider [15].

Sewage sludge often contains nitrogen, phosphorus and other trace elements that can promote miscanthus growth. This can help reduce the need for commercial fertilizers.

Adding sediment can improve soil structure, increasing its organic content and helping to retain moisture. It is important to consider the possible content of harmful substances in biosludge, such as heavy metals, pathogens or residues of pharmaceuticals. These substances can be harmful to the environment and human health [3, 16, 17].

Regular soil and plant monitoring may be necessary to ensure that nutrient and potentially harmful constituents are within safe limits.

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3. Purpose and objectives of the study

The use of sewage sludge in agriculture is often regulated by legislation that requires compliance with certain treatment and application standards and procedures. The task of our research is to treat sewage sludge before its introduction to reduce the risk of contamination and ensure its safe use. The purpose of our study is the effect of sewage sludge on miscanthus yield, it can help determine the optimal levels of its application and provide recommendations for the practical use of an energy crop with high energy value with the introduction of a certain dose of fertilizer.

Using sewage sludge as fertilizer for miscanthus can be an effective way to recycle organic waste.

4. Research methods

Field experiments were conducted in the West of our country, namely in the territory of the Ivano-Frankivsk region, village Tsenzhiv Yamnytska Yamnytska united territorial community (figure 1).

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Figure 1. The area where field research was carried out.

The scheme of field experiments included the following options (figure 2):

1. Without fertilizers – control;
2. $N_{60}P_{60}K_{60}$;
3. $N_{90}P_{90}K_{90}$;
4. $SS - 20$ t/ha $+ N_{50}P_{52}K_{74}$;
5. $SS - 30$ t/ha $+ N_{30}P_{33}K_{66}$;
6. $SS - 40$ t/ha $+ N_{10}P_{14}K_{58}$;
7. Compost $(SS + straw(3:1)) - 20$ t/ha $+ N_{50}P_{16}K_{67}$;
8. Compost $(SS + straw(3:1)) - 30$ t/ha $+ N_{30}K_{55}$ [6].

Figure 2. Cultivation of miscanthus.

Planting scheme of giant miscanthus – 0.50 x 0.70 m. Planting of rhizomes was carried out by hand, wrapping them in the soil to a depth of 10 – 15 cm. Width of the experimental plot – 5.0 m; length – 7 m. The total area of the experimental site – 63.0 m^2, the accounting area – 35.0 m^2. The number of rows is 10. The number of rhizomes in a row is 10 pcs. [9].

The research results were processed using the methods of mathematical statistics using the programs STATISTICA 12 for Windows, MathCAD 15 and MS Excel 2010. Primary materials included analysis using linear regression equations [9].

In our studies, the efficiency of miscanthus cultivation was determined as the ratio of the gross energy accumulated by the crop to the energy costs for the production of biomass per unit area:

$$Kee = Ei/Ec$$

Kee is the coefficient of energy and efficiency of growing phytoenergy crops. Reflects how efficiently miscanthus plants are grown for energy production. It takes into account the different stages of growing, harvesting and processing biomass. Ei is the energy intensity of the biomass of the grown crop, MJ/ha. Ec – energy costs for growing miscanthus, also measured in MJ/ha. This value describes the energy used to grow crops, including all processes from soil preparation to harvest [6].

The amount of gross energy:

$$GE = Y \cdot Kc \cdot q_{pr}$$

It was used to assess the energy efficiency of growing phytoenergy crops and increase the efficiency of biomass production processes for energy needs.

5. Research results

Miscanthus (Miscanthus x giganteus) is a perennial crop that is grown in America and Western Europe as one of the sources for the production of solid biofuel.

Due to the high yield of dry biomass (up to 25 t/ha), high calorific value (5 $kW/h/kg$ or 18 MJ/kg), low natural humidity of the stems at the time of harvesting (up to 25%), miscanthus is the most effective, compared to others agricultural crops.

The conducted studies show that the biomass of miscanthus grows proportionately during the growing season, starting from May and ending in September.

Accordingly, every year the collection of miscanthus biomass increased and the energy output increased with the harvest. After 4 years of cultivation, the biomass collection was high, therefore, in the control without fertilizers, the energy output was 186 GJ/ha, with the application of mineral fertilizers in a dose of 60-90, the energy output was 193-200 GJ/ha, respectively. In particular, with the application of fresh sewage sludge in combination with mineral fertilizers, the energy output increased and was the highest in the version where SS was applied at a dose of 40 t/ha and mineral fertilizers $N_{10}P_{14}K_{58} - 231$ GJ/ha.

Composting reduced energy output compared to options where fresh sewage sludge was applied, but remained higher compared to the no-fertilizer control. Therefore, the energy yield of miscanthus was the lowest in the control without fertilizers (figure 3).

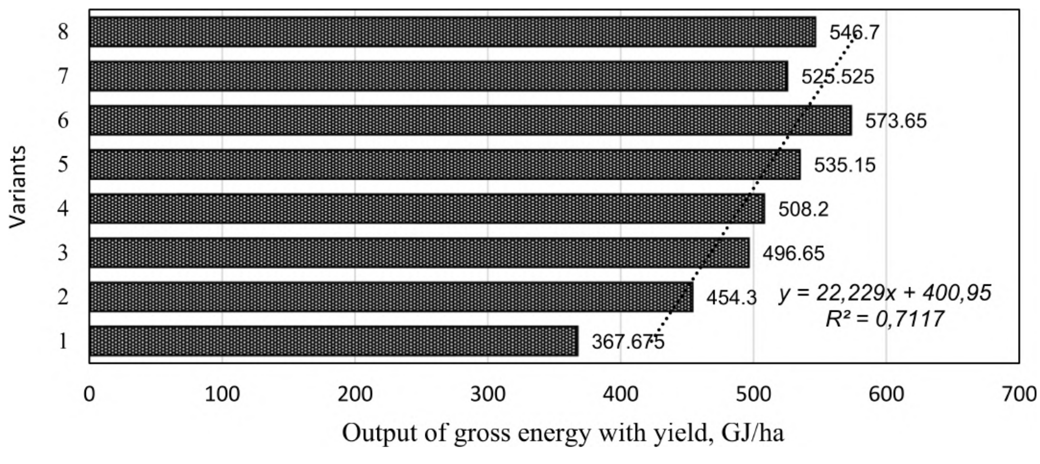

Figure 3. General view of the rod magnetic flaw detector in working condition.

Analyzing the economic efficiency of the production of miscanthus biomass table 1, it should be noted that it is quite profitable at 3805 UAH/ha and profitable at 58.05% at the same time at a low cost of 529 UAH/t, which involves planting the crop on sod-podzolic soils with the application of fertilizer based on SS in a dose of 40 t/ha and mineral fertilizers $N_{10}P_{14}K_{58}$.

Table 1. Output of energy and solid biofuel from obtained miscanthus biomass, average 2020-2022.

Variants	Yield of dry biomass, t/ha	Yield of solid biofuel, t/ha	Output of gross energy with yield, GJ/ha
Control – without fertilizers	19.1	21.01	367.67
$N_{60}P_{60}K_{60}$	23.6	25.96	454.34
$N_{90}P_{90}K_{90}$	25.8	28.38	496.65
SS–20t/ha + $N_{50}P_{52}K_{74}$	26.4	29.04	508.24
SS–30t/ha + $N_{30}P_{33}K_{66}$	27.8	30.58	535.15
SS–40t/ha + $N_{10}P_{14}K_{58}$	29.8	32.78	573.65
Compost(SS + straw(3:1))–20t/ha + $N_{50}P_{16}K_{67}$	27.3	30.03	525.52
Compost(SS + straw(3:1))–30t/ha + $N_{30}P_{55}$	28.4	31.24	546.76

The energy yield decreased with the application of composts compared to the options where fresh SS was applied, but remained higher compared to the no-fertilizer control. Therefore, the energy yield of miscanthus was the lowest in the control without fertilizers.

The Shapiro-Wilk test is equal to 0.97. According to the obtained results, with a probability of 97 percent, the distribution is normal.

At the same time, the p-level in this analysis is greater than 0.05 – (namely, 0.81) – the null hypothesis about the absence of a normal distribution of data can be rejected. The Kolmogorov-Smirnov clarifying (control) criterion confirms the assumption about the normality of the distribution – the p-level of this criterion is greater than 0.2 (figure 4).

Since the options for the introduction of SS directly affected the change in gross energy output with the yield of giant miscanthus, the regression model of gross energy output can be described by the following equation:

$$y = 22.229x + 400.95,$$

where y is the output of gross energy with yield, GJ/ha; x – rules for introduction of SS.

The multiple coefficient of determination was $R^2 = 0.7117$, which indicates a close relationship between the application rates of SS and gross energy output with the yield of giant miscanthus.

6. Discussion of the results

A comparative analysis of the table shows that the application of fertilizers significantly affects the production of dry biomass of miscanthus. The option without fertilizers gives the lowest biomass yield, 19.1 t/ha. The use of mineral fertilizers ($N_{60}P_{60}K_{60}$ and $N_{90}P_{90}K_{90}$) improves this indicator to 23.6 and 25.8 t/ha, respectively. The combination of SS with mineral fertilizers further increases the yield of biomass, reaching a maximum value of 29.8 t/ha at the highest application dose of SS. Variants with compost also show high results, emphasizing the efficiency of using organic waste for growing miscanthus on sod-podzolic soils.

Analysis of dry biomass yield indicators for each research option demonstrates that fertilizer application increases biomass production. Variants with mineral fertilizers ($N_{60}P_{60}K_{60}$ and

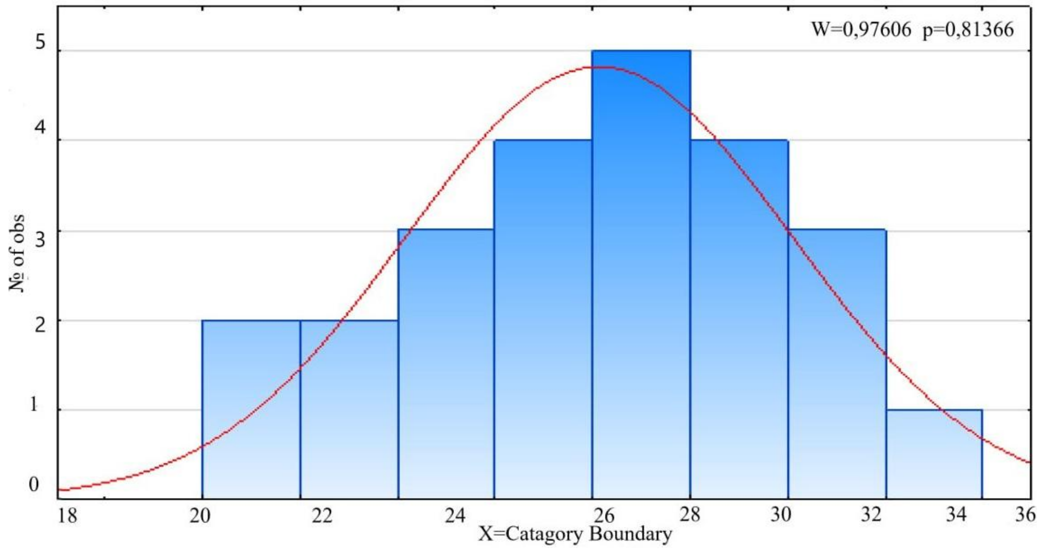

Figure 4. Normal distribution of solid biofuel yield data for miscanthus cultivation.

$N_{90}P_{90}K_{90}$) show moderate growth compared to the unfertilized control. The application of SS further increases biomass yield, with a significant increase in the use of SS doses. Compost combining SS and straw also has an effective effect on biomass production, highlighting the usefulness of integrating organic waste for growing energy crops using the example of miscanthus.

A detailed comparative analysis of the yield of solid biofuel from miscanthus shows that the application of fertilizers contributes to an increase in the yield of dry mass. Without fertilizers, 21.01 t/ha of biofuel is produced. With mineral fertilizers ($N_{60}P_{60}K_{60}$), the yield increases to 25.96 t/ha, and with more mineral fertilizers to 90 t/ha ($N_{90}P_{90}K_{90}$), the yield of solid biofuel is 28.38 t/ha. Variants with SS show even more growth, especially at high doses (SS – 40 t/ha), reaching 32.78 t/ha. Composting with SS also improves yield, from 30.03 t/ha to 31.24 t/ha, depending on the amount of compost and fertilizer.

The relationship between dry biomass output and gross energy of miscanthus can be expressed in the form of a linear regression model as follows:

$$y = 18.2909 + 0.0184x,$$

where y is the content of dry biomass, t/ha; x – gross energy output, GJ/ha.

The study of the relationship between the output of gross energy and the content of dry mass of miscanthus (figure 5) indicates the value of the coefficient of determination ($R^2 = 0.59$). The correlation coefficient $R = 0.71$ indicates a moderately strong positive correlation.

It was established that the coefficient of energy efficiency depends on the yield of dry biomass of miscanthus and the yield of gross energy (figure 6).

Such correlation dependence can be expressed by the regression equation:

$$z = 22.8094 - 1.6169 \cdot x + 0.0099 \cdot y + 0.0224 \cdot x \cdot x + 0.0007 \cdot x \cdot y - 2.7132E - 5 \cdot y \cdot y,$$

where z is the energy efficiency coefficient; x – yield of dry biomass, t/ha; y – gross energy output, GJ/ha.

Taking this into account, it can be argued that the application of SS with a compensatory dose of mineral fertilizers is an extremely effective way of increasing the biomass of energy crops, for example miscanthus.

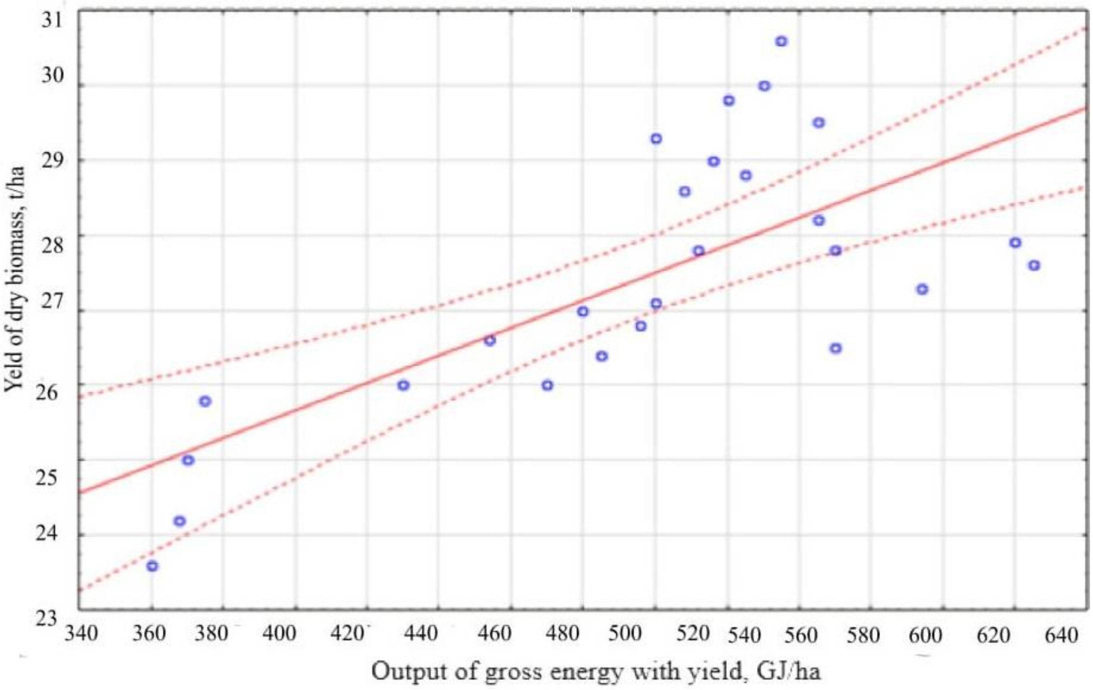

Figure 5. Dependence of the output of gross energy on the output of dry mass of miscanthus.

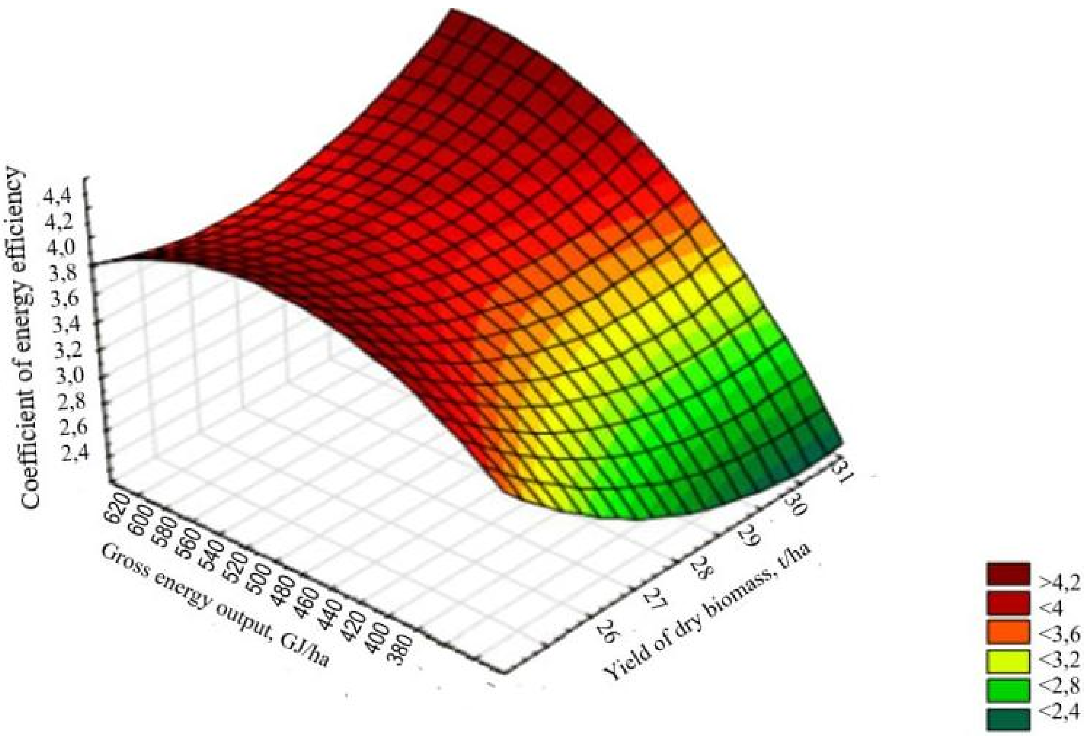

Figure 6. Dependence of the energy efficiency coefficient on the yield of dry biomass of miscanthus and the yield of gross energy.

7. Conclusions

Thus, according to our research, the application of sewage sludge for the cultivation of energy crops, using the example of miscanthus, increases the yield (yield of dry mass) from 19.1 t/ha to 28 – 30 t/ha, depending on the application rates of SS and composts based on SS.

A detailed comparative analysis of the yield of solid biofuel from miscanthus shows that the application of fertilizers contributes to an increase in the yield of dry mass. Without fertilizers, 21.01 t/ha of biofuel is produced. With mineral fertilizers ($N_{60}P_{60}K_{60}$), the yield increases to 25.96 t/ha, and with more mineral fertilizers to 90 t/ha ($N_{90}P_{90}K_{90}$), the yield of solid biofuel is 28.38 t/ha. Variants with SS show even more growth, especially at high doses (SS – 40 t/ha), reaching 32.78 t/ha. Composting with SS also improves yield, from 30.03 t/ha to 31.24 t/ha, depending on the amount of compost and fertilizer.

It is advisable to pay attention to the increase of the energy efficiency coefficient with the application ($SS-40$ t/ha $+N_{10}P_{14}K_{58}$ and Compost $(SS+straw(3:1))-20$ t/ha $+N_{50}P_{16}K_{67}$) from 3.3 to 4.1. It is with the introduction of fertilizer with such a norm of SS 40 t/ha and composts based on SS at a rate of 20 t/ha that increases the output of gross energy to 547 – 578 GJ/ha.

The relationship between the output of gross energy and the content of dry weight of miscanthus was studied, the coefficient of determination ($R^2 = 0.59$) and the correlation coefficient $R = 0.71$, which indicates a moderately strong positive correlation.

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Application of polymer flooding to increase oil recovery

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Application of polymer flooding to increase oil recovery

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Abstract. This article examines the problem of non-uniform oil displacement during the development of multi-layer fields and proposes a promising approach to solve it – polymer flooding. The article outlines the basic principles of polymer flooding, including dissolving polymers in water to increase viscosity and reduce water mobility. Various types of polymers used in this technology and their unique characteristics are considered. The advantages of polymer flooding are highlighted, such as increasing reservoir coverage and increasing oil production efficiency. The illustrations presented in the article compare oil displacement using polymer flooding and traditional methods. In conclusion, a comparative description of various types of polymers in terms of composition and main application parameters is given and the importance of this technology in the context of ensuring sustainable and efficient oil production in multi-layer fields is substantiated.

1. Introduction

The development of multilayer fields is a complex process, which is often accompanied by heterogeneous oil displacement, especially in low-permeability zones. This factor can lead to oil retention in the rocks, which negatively affects production efficiency. To solve this problem, various technologies are used, one of which is polymer flooding (PF).

Polymer flooding is a technology aimed at increasing oil recovery by improving the water sweep factor using polymers. The basic idea is to dissolve polymers in water, which increases the viscosity of the water and reduces its mobility. As a result of the use of polymers, flow-diverting screens are created that promote uniform penetration of water into the rock. There are several types of polymers used for polymer flooding: cross-linked polymer composition (CPC); polymer disperse composition (PDS); polymer-gel system (PGS); cellulose ether (PEC); biopolymers (BP); alkaline-surfactant-polymer flooding (ASP) flooding [1, 2].

Oil that was retained by capillary forces or was not captured remains in the formation. The PF facilitates the recovery of residual oil. The polymer solution penetrates into highly permeable interlayers, as a result of which the dynamic heterogeneity of fluid flows decreases and, accordingly, the coverage of the formation by flooding increases.

If displacement is ineffective, water breaks through to production wells, which contributes to an increase in water cut. In this case, the ratio of oil and water mobilities is unfavorable,

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so injection of polymer into the reservoir will increase the sweep factor. The causes of breakthroughs can be zonal and layered heterogeneity of the formation, occurrence of bottom water, the presence of highly permeable cracks or channels (especially typical for fractured-porous reservoirs), as well as leakage of the production casing. If the formation has some heterogeneity and a favorable ratio of mobility, then with PF it is possible to extract oil from formations with low permeability [3, 4].

When using PF, greater oil displacement occurs compared to traditional waterflooding, which illustrates (figure 1). PF consists of mixing water and polymer and injecting this solution into the formation. The solution must be injected until the polymer fills 1/3–1/2 of the pore space of the reservoir. Typically solutions consist of 40-50 % polymer components.

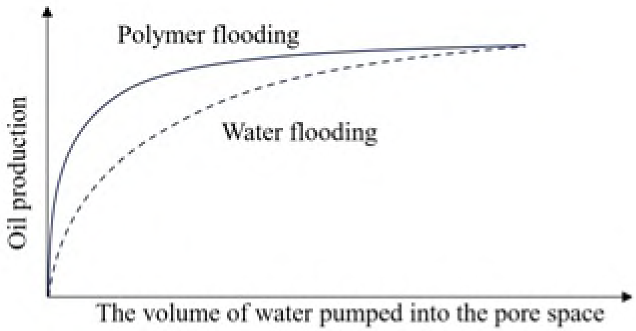

Figure 1. Comparison of polymer and conventional flooding [5].

Water that is injected into the formation tends to take the path of least resistance to neighboring production wells, i.e. get into an area where there is higher permeability and lower pressure. If the viscosity of the injected water is less than the viscosity of the oil, then the water will pass through or bypass the oil. All this leads to a decrease in the reservoir flooding coefficient, and a decrease in oil recovery will also be observed [6].

When choosing a polymer, it is necessary to consider the geological and physical conditions of application for polymer flooding. The range of geological and physical conditions has recently expanded significantly. This is since developments in petrochemicals have made it possible to adapt polymers and make them more resistant to reservoir temperature, formation water salinity and shear factor. Special protective additives are also added to make the polymers more resistant to harsh environments.

New research in the field of PF, considering the specifics of reagent injection into the reservoir, reduces the risk of polymer destruction and increases the efficiency of technology application. Currently, PF is carried out at high temperatures, salinity and in formations with heavy oil. In table 1 an example of polymer flooding parameters is presented.

Reservoir permeability, reservoir temperature and water salinity play an important role when using polymer flooding. Because ions such as calcium Ca^{2+} and magnesium Mg^{2+} are present in carbonate reservoirs, precipitation of the polymer with calcium and magnesium salts occurs in these reservoirs. All this negatively affects the waterflooding process [7].

The permeability of the rock affects the rheological properties of the polymer during filtration in a porous medium. A decrease in permeability entails an increase in the rheological properties of solutions. This has a particularly strong effect on the residual resistance factor. Using this parameter, it is possible to evaluate the effect of the polymer. The resistance factor is associated with the adsorption of the polymer by rocks. Adsorption is the process of rocks absorbing dissolved substances from the environment. The decrease in formation permeability for the polymer solution is much stronger than the change in the viscosity ratio of oil and

Table 1. Example of polymer flooding parameters.

Reservoir characteristics	Current application range
Permeability, μm^2	0.01-2.0
Temperature, $^\circ C$	80-120
Lithological composition	Sandstone
Viscosity of oil in the reservoir, $Pa{\cdot}s$	Less than 10
Oil density, kg/m^3	More than 965.9
Mineralization, g/l	Less than 270
Oil saturation, %	More than 20

water. This is called the resistance factor. The residual resistance factor is a parameter showing that even after complete destruction of the polymer, the permeability of the formation is not completely restored. If the permeability is less than 0.01 μm^2, then the polymer flooding process is practically impossible, since the polymer dimensions are larger than the pore sizes. As a result, clogging of the bottomhole zone occurs – mechanical blocking of cracks and fluid penetration channels [7, 8].

Possessing high viscosity, polymer solutions are capable of displacing oil and bound water from porous media. As a result, interaction occurs with the skeleton of the porous medium (with rock and cementitious substance). This process is called polymer adsorption (figure 2). During the adsorption process, polymer molecules are deposited on the surface of the medium and the channels are clogged, i.e. water filtration deteriorates. The mineralization of water and the mineral composition of the rock affect the amount of adsorption. To reduce adsorption, there is a need to create a freshwater rim.

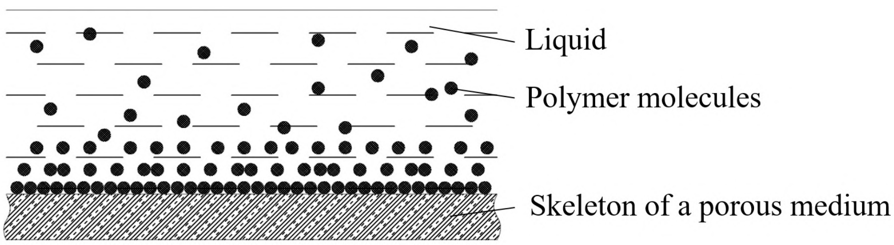

Figure 2. Polymer adsorption.

There is a range of adsorption values at which the flooding process will be most effective. The minimum flooding effect will be observed at zero adsorption, as can be seen from figure 3.

This dependence can be explained by the fact that the polymer solution in the formation is mixed with bound water and destroyed. This leads to a decrease in viscosity. As a result of this process, a zone of inactive water is formed. However, the task of the polymer solution is to increase the viscosity of water and reduce its mobility, as well as to increase the resistance factor at a low filtration rate of the solution, which can ensure the process of polymer adsorption. Thus, a decrease in adsorption reduces the formation resistance factor for water, and reduces the coverage of the formation by waterflooding, which makes the waterflooding process insufficiently effective.

On the other hand, with high adsorption, a decrease in oil recovery is observed. The front of oil displacement by polymer lags the front of displacement by water; accordingly, most of the oil is displaced by inactive water. As a result, oil recovery from the reservoir is reduced. Therefore,

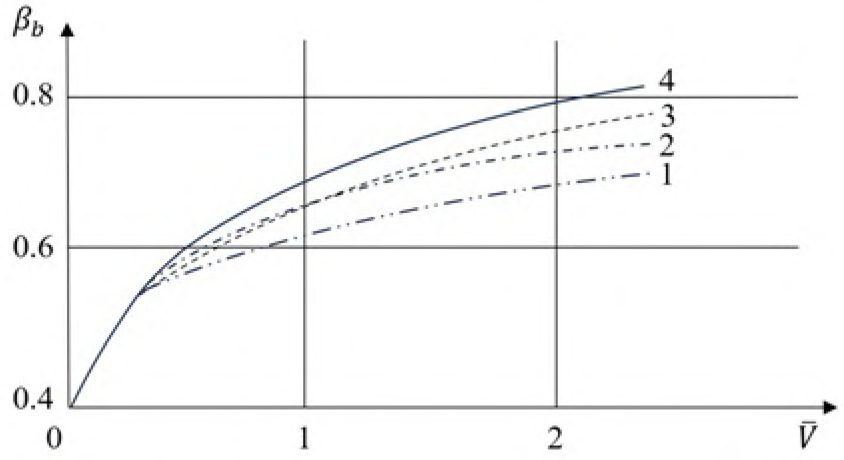

Figure 3. Dependence of displacement coefficient on relative selection at different polymer sorption properties (displacement occurs): 1 – water; 2, 3, 4 – polymer solution with different desorption coefficient 0; 1 and 0.5 respectively.

for the most effective displacement, it is necessary to select the optimal polymer adsorption [9].

The polymer loses stability at high reservoir temperatures, so it is necessary to add stabilizers. These substances can increase the polymer's resistance to temperature and prevent the polymer from precipitating from solution. From figure 4 at the same temperature the viscosity ratio will be lower, the lower the concentration of the solution. This graph also shows that solution concentration and temperature affect the viscosity coefficient.

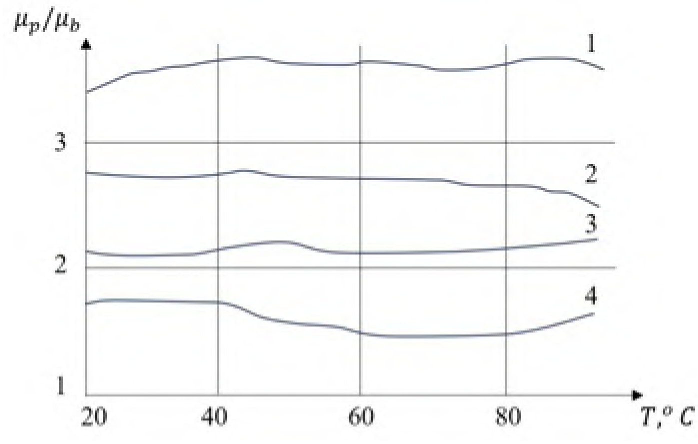

Figure 4. Effect of temperature on the ratio of viscosities of the polymer solution and water at various concentrations. Concentration, %: 1 – 0.1; 2 – 0.05; 3 – 0.03; 4 – 0.015.

The temperature situation in the reservoir can be tracked by the geothermal gradient, i.e. the increase in reservoir temperature per 1 m depth, and the geothermal stage – the reciprocal value of the geothermal gradient. In the subsurface there are not only areas with normal temperatures, but also areas with abnormal temperatures. The magnitude of the geothermal gradient decreases in synclinal zones and increases in anticlinal zones. Thus, synclines are zones of low temperature. This is explained by the fact that in areas of synclinal depressions and troughs, clayey rocks predominate, which, in turn, have lower thermal conductivity. Anticlines are zones of increased temperature. These anomalies are caused by the fact that within the uplifts the sand section predominates, which has increased thermal conductivity. Elevated temperatures are temperatures above 95 °C with a gradient above 4 °C/100m.

Changing the temperature in the formation leads to changes in the volumes of liquid, gas, and host rocks. As a result of increasing temperature, the viscosity of oil and water decreases and the viscosity of gas increases. Reservoir pressure increases with increasing temperature in a closed reservoir. Changes in phase relationships in deposits and the solubility of gases in water and oil, as well as salts in water, are associated with reservoir temperature. A decrease in reservoir temperature entails complications in the production of hydrocarbons and leads to the loss of valuable products (viscous oil, condensate, and paraffin), therefore, the development of oil fields is carried out with an increase in reservoir temperature [10, 11].

The pressure for injecting polymer solutions into the formation must be higher than the pressure of conventional flooding. Accordingly, the optimal pressure should be 20-22 MPa. Such pressure is necessary to maintain reservoir pressure due to an increase in the viscosity of the displacing agent, the appearance of additional resistance of the medium, and due to the manifestation of the apparent viscosity of the solution. For these reasons, PF will be ineffective in low-permeability formations. During filtration through a porous medium, apparent viscosity appears in the solution, as mentioned above. The viscosity turns out to be 10-20 times higher than the viscosity measured by a viscometer. As a result, it is more effective to apply PP for oil with high viscosity to increase the reservoir flooding coefficient [12].

When mixing the polymer and formation water, destruction of molecules is observed and, accordingly, a decrease in viscosity. If formation water has high mineralization, then the polymer concentration should be 2-3 times higher. However, for effective polymer flooding it is better to use low-mineralized water with a low content of calcium and magnesium [13].

The current reservoir pressure maintenance system is in-line waterflooding. It should also be considered that when the water cut of the product is more than 80%, the use of PF becomes ineffective. This is explained by the fact that, under these conditions, the filtration resistance of the porous medium practically does not change when using the polymer [13, 14].

Thus, the choice of polymer and/or polymer protection is an important part of the PF process. The most important parameters that polymers must satisfy are formation temperature, formation permeability and salinity of injected water. It is necessary to pay due attention to such a geological and physical parameter as reservoir temperature. To improve oil recovery, the stability of the reagents determines the duration of the flooding effect; accordingly, the reagent must be resistant to elevated reservoir temperatures [15, 16].

2. Comparative analysis of chemical reagents and formulations

For the greatest efficiency from the use of PF, it is necessary to carefully study the geological and physical conditions and, based on these conditions, select the optimal composition of the reagent. Polymers, like many other reagents, have their own properties. These properties determine the field characteristics of the use of polymers:

1. Viscosity – anionic polyacrylic acid (PAA) have a thickening ability, which is associated with the interaction of macromolecules with high molecular weight. This parameter depends on the concentration and molecular weight of the polymer in solution.
2. Rheological properties – solutions based on PAA are characterized by non-Newtonian behavior, i.e. The viscosity of the solution depends on the applied shear stress. The solution exhibits pseudoplastic behavior in which the viscosity decreases with increasing shear stress.
3. Solubility – problems with solubility and filtration capacity will be observed when using polymers with high (more than 1 million g/mol) or ultra-high (about 18 million g/mol)

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molecular weights.

Thus, the following requirements are identified when choosing a polymer:

- High viscosity;
- Good solubility;
- Reduced degree of polymer retention in the formation;
- Resistance to mechanical destruction, i.e. shear resistance;
- Resistance to chemical degradation, i.e. use of protective systems to minimize the amount of impurities in water;
- Resistance to thermal degradation, i.e. adding stabilizers to the solution;
- Resistance to biological destruction, use of biocides (substances that can fight harmful organisms);
- Good filterability, i.e. good polymer transfer in a permeable environment.

Polymers entering the formation reduce the permeability of the formation, therefore the optimal polymer concentration is 0.1-0.15% by weight. Using a higher concentration is unprofitable, since a significant decrease in permeability will be observed [17].

Currently, due to the wide variety of reagents in petrochemistry, the following types of polymers are distinguished: cross-linked polymer composition; polymer dispersed composition; polymer-gel system; cellulose ether; biopolymers and ASP flooding [18].

2.1. Cross-linked polymer composition

Cross-linked polymer composition (CPC) is aqueous gels based on water-soluble polymers, which can be used to increase reservoir coverage by flooding. Most often, PAA is used as a water-soluble polymer. CPC is most effective at the third stage of development. At this stage, there is a decrease in oil production and an increase in the water cut of products.

When PAA is injected into the formation, it is possible to reduce the mobility of water and increase its viscosity, and it is also possible to increase the coverage of the formation by flooding. The formation of CPC is the result of chemical crosslinking of polymer macromolecules (crosslinkers) with solvent (water) molecules. Chromium acetate ($Cr(CH_3COO)_3$) or aluminum citrate ($[C_3H_4OH(COO)_3]Al$) are mainly used as a crosslinker. The formation of a gel consisting of cross-linked polymer chains in a solvent occurs during the reaction. The gelation time may be greater than or equal to the time of injection of the composition into the formation. The viscosity of the solution increases during the crosslinking stage [19].

The cross-linked polymer composition is capable of penetrating deep into the formation over significant distances, which contributes to the effective regulation of filtration flows. This composition has high apparent viscosity, as well as viscoelastic and viscoelastic properties. All these properties ensure more effective use of this technology compared to other compositions. Result of applying ATP:

- Redistribution of filtration flows;
- Water inrush containment;
- Introduction of hard-to-recover reserves into development;
- Increased oil production.

2.2. Polymer dispersed composition

Polymer dispersed composition (PDS) is a complex consisting of a polymer solution (usually PAA) and a suspension of mineral particles (clays). This polydisperse complex makes it possible to block water-saturated layers, because of which it is possible to influence low-permeability areas of the formation and involve them in development.

The process of formation of PDS is complex and includes several stages: adsorption of polymer and clay particles on the rock surface, flocculation, and filtration. In this composition, PAA molecules act as both a stabilizer and a flocculant. Polymer molecules enter the formation before the clay particles and are adsorbed and retained on the rock surface, so the concentration of the polymer in the solution decreases. Stabilization of a clay suspension occurs at high concentrations of polymer in solution. As the polymer concentration in the solution increases, the precipitation of particles from the solution slows down. As the polymer concentration decreases, the rate of deposition of clay particles increases. Under the action of PDS, flocculation of a suspension of clay particles occurs, which occurs when mixed with a PAA solution. PAA molecules form flocs, being fixed between clay particles. During these processes, clay particles are retained in the pore space and block highly permeable layers. Thus, with the help of PAA, it is possible to regulate the deposition of the clay suspension in the formation.

The effect of this system is to increase the filtration resistance of flooded zones, increase the coverage of the formation by waterflooding and increase oil production.

Currently, a modified polymer disperse composition (MPDS) is also used. MPDS, which has structural and mechanical properties, consists of a polymer, a cross-linking agent (AMG) and clay particles. This composition makes it possible to increase oil production from heterogeneous formations with large washed out zones.

Injection is carried out by sequential alternation of the PAA slug and the clay suspension. A crosslinking agent is also pumped in at the same time. AMH is introduced into clay and polymer particles. Clay suspension particles interact with PAA [20].

2.3. Polymer-gel system

The polymer-gel system (PGS) consists of a one-component gel system, which is based on PAA; therefore, PGS is based on intramolecular cross-linking of molecules. This system is resistant to mechanical destruction, and the system is also stable in waters with high mineralization and thermal-oxidative stability.

Due to its high viscoelasticity, PGS can reduce the amount of residual oil in the reservoir. Also, because the ASG has small particle sizes, this system can penetrate deep into the formation, thereby increasing the coverage of the formation by waterflooding.

PGS has high thermal stability and salt resistance, which increase the effective time of use of this composition. Due to the possibility of deformation into thin threads from the sphere and vice versa, the use of PGS makes it possible to slow down the movement of the composition slug through the formation [21].

2.4. Cellulose ether

Cellulose ether (CEC) can also be used in conjunction with a polymer to apply PF technology more effectively. This composition can be used at a late stage of development. If a polymer solution with CEC without a crosslinker is used at an early stage of development, thickening of the water will be observed, but without the formation of a gel. Due to a decrease in the mobility of the displacing agent, the displacement front is leveled, i.e. reservoir coverage by flooding increases.

With high water content of the product, which is typical for the late stage of development, the addition of metals entails the formation of a gel. As a result of the formation of the gel, the flow of water into the flushed zones is blocked and the displacing agent is directed to zones that were not previously covered by flooding. When injecting large volumes of CEC polymer solutions (2000 m^3 or more), redistribution of filtration flows occurs not only in the near-wellbore zone, but also in more distant parts of the formation.

For better cross-linking, polyvalent metals (chromium Cr, manganese Mn, iron Fe) are added to the CEC polymer solution. The mobility of the formed gel decreases when reservoir water is pumped into the formation, as well as when the PEC polymer solution is mixed with highly mineralized water [22].

The following cellulose ethers are used for flooding:

- Carboxymethylcellulose (cellulose glycolic acid) – $[C_6H_7O_2(OH)_2(OCH_2COOH)]_n$;
- Methylcellulose – $[C_6H_7O_2(OH)(OCH_3)_2]_n$;
- Ethylcellulose – $[C_6H_7O_2(OH)(OCH_2CH_3)_2]_n$;
- Hydroxyethylcellulose – $[C_6H_7O_2(OH)_2(OCH_2CH_2)OH]_n$ and others.

2.5. Biopolymers
The development of biotechnology has made it possible to use biopolymers (BP) in the oil industry. This type of polymer is polysaccharides of plant and microbial origin.

The possibility of using this type of polymer lies in the fact that at low concentrations the biopolymer can change the rheological properties of aqueous systems, namely: increasing viscosity and forming gels. Biopolymers can be used in harsh environments where the use of synthetic polymers is ineffective.

There are several types of biopolymers: plant and microbial. Plant polysaccharides have a significant drawback – the impossibility of obtaining the reagent in the required volume at different times of the year and in different climatic conditions. Polymers are resistant to different pH environments (acidic and alkaline). Biopolymers have an important property – resistance to destruction. However, biological destruction prevents the effective use of this composition since they can be destroyed by microorganisms during storage and direct use [23].

2.6. ASP flooding
In recent years, alkali-surfactant-polymer stimulation of the formation is often used, which is called ASP flooding. This type of polymer flooding includes several components: polymer, anionic surfactant and soda.

When using this PF, a double effect on the formation occurs: soda and surfactants reduce interfacial tension due to the formation of a microemulsion, while the polymer, in turn, increases oil mobility. Surfactants reduce the capillary forces that hold oil in the small pores of the rock. With the help of a polymer, the coverage of the reservoir by flooding is increased. This type of protection zone is the most effective since each component of the composition has its own effect on the formation. The use of ASP flooding allows the user to increase the amount of oil and reduce the amount of produced water, however, the number of extracted hydrocarbon fluids does not change. The use of this technology will increase oil recovery factor by 10% in the field [24].

3. Conclusions and recommendations
Using polymer flooding, you can increase reservoir coverage and improve oil recovery. In this case, the main parameters influencing the choice of polymer flooding technology are the characteristics of the formation and the high viscosity of the oil.

To achieve the greatest efficiency, an integrated approach to the use of polymer flooding is important. It is necessary to carefully study the geological and physical conditions in which the technology will be applied. The most important formation parameters are temperature (80-120 $°C$), permeability (0.01-2.0 μm^2) and formation water salinity (less than 270 mg/l). The viscosity of the oil also plays an important role – the higher the viscosity of the oil in reservoir conditions, the more effective the impact on the reservoir will be. In carbonate reservoirs, the use of polymer flooding is complicated by the presence of calcium Ca^{2+} and magnesium Mg^{2+} ions in the reservoir. The ions can react with polymers, resulting in the deposition of the polymer on the rock surface.

The variety of research in petrochemistry leads to many compositions for polymer flooding. Developments make it possible to adapt polymers for their use in abnormal reservoir conditions. The following types of polymer compositions are distinguished: cross-linked polymer composition; polymer dispersed composition; polymer-gel system; cellulose ether; biopolymers; ASP flooding. Table 2 a comparative description of various types of polymers is given in terms of composition and main application parameters – temperature and permeability. The features of the use of each composition are also highlighted.

The most effective polymer production technology is copolymerization. The optimal polymer concentration in solution is 0.1-0.15% of mass.

The technological mode of injection of a polymer solution into the formation plays an

Table 2. Comparative table of polymers.

Name	Compound	Temperature, $°C$	Permeability, μm^2	Application	Peculiarities
THX	PAA+ Crosslinker	$\leqslant 80$	0.03-0.5	At a late stage development	1. Penetrates deeply into the formation; 2. High apparent viscosity.
PDS	PAA + Clay solution	$\leqslant 80$	0.2-2.0	Heterogeneous formations in large washed-out zones	Structural-mechanical properties
PGS	PAA+ Crosslinker	$\leqslant 90$	0.03-0.5	Waters with high mineralization	1. Resistance to mechanical destruction; 2. Thermal-oxidative and thermostable stability; 3. Salt resistance; 4. Penetrates deeply into the formation.
PEC	Polymer+ Cellulose ethers	$\leqslant 100$	0.03-0.5	At a late stage development	1. Good binding, wetting and adhesive ability; 2. Redistribution of flows in the reservoir zone and the remote part of the reservoir.
TSA	Polymer+ Alkali+ Surfactant	-	-	High water cut	1. Double impact on the formation; 2. Non-toxic.
BP	Polymers of natural origin (polysaccharides)	$\leqslant 130$	0.01-0.2	Abnormal reservoir conditions	1. Resistance to destruction; 2. Resistance to different pH environments.

important role. It is necessary to deliver the polymer to the desired location in the formation and prevent its destruction. The optimal injection pressure is 20-22 MPa. When the water cut is more than 80%, it is not advisable to use polymer flooding.

A negative process that can accompany polymer flooding is polymer destruction. It is important to prevent the premature onset of this process. To do this, it is necessary to add thermal stabilizers to the polymer solution to prevent the onset of thermal destruction. To prevent chemical degradation, it is necessary to use high-quality water for flooding, i.e. water for flooding must be oxygen-free or with a minimum oxygen content (less than 0.5 mg/l). The risk of mechanical destruction can be minimized by maintaining a fluid flow rate of no more than 5 m/s biological destruction is extremely rare. Also, this type of destruction does not affect the viscosity of the solution.

Currently, polymer solution technologies using ASP flooding or cellulose ether are gaining popularity. Examples of fields where these technologies were applied were considered. The composition for ASP flooding includes 3 components: polymer, alkali, and surfactant. Each component has its own effect on residual oil. This composition is more effective, since because of the composition on the formation, oil production increases and the amount of produced water decreases. Polymer flooding with the addition of cellulose ether is also quite effective. This is explained by the fact that cellulose ether increases viscosity in aqueous solutions, which has a positive effect on the flooding process.

The cross-linked polymer composition has several advantages over other compositions. This composition can also be used at later stages of development. Also, the cross-linked polymer composition is capable of penetrating deep into the formation over long distances. This makes it possible to more effectively influence filtration flows.

Thus, with the help of polymer flooding technology, it is possible to increase the flood coverage of the reservoir and recover residual oil from the reservoir. This technology makes it possible to level the oil displacement front and extend the water-free period of field operation. It is important to choose the correct composition of the polymer solution. It is also necessary to observe the technological regime of injection of the solution into the formation to prevent premature destruction of the polymer and achieve the greatest effect from polymer flooding.

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Transformation of the business ecosystem model into energy enterprise's strategy

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Abstract. The purpose of the article is to characterize the relevance, structure and background of business ecosystem model working out and its implementation at energy companies and to determine the ways of its interconnected and interdependent components transformation into enterprises' strategy. It's proved that formation of a business ecosystem model of energy company is an activity based on combining the efforts of interested parties, which, on the one hand, is aimed to achieve business goals, meet the energy resource needs of various groups of consumers, and on the other hand, on the complying with conditions that ensure the balance of their activities for the realization of the goals of sustainable development and the development of measures to maintain the ability of the business ecosystem to preserve its structure and functionality under the influence of external factors, taking into account global energy trends and energy development strategies. The focus is maid on the business ecosystem model those components integrate business processes, natural ecosystems and people efforts. It is emphasized that the transformation is a process of fundamentally changes based on the application of transformation tools, the choice of which depends on the selected type of transformation: emergency, innovative and evolutionary. Transformation processes require stakeholders' cooperation with, that shifts the traditional orientation of energy companies' activities mainly from economic results and business interests to the taking into account the benefits of an ecosystem approach, which accomplish with the added value by reducing the harm to the environment as well as the creating, in some way the business opportunities. It is justified that consideration of issues of collaboration and communication in transformation acquires special importance, since the achievement ofstrategic goalsinvolvesthe interested participants and the achievement of understanding and interaction in the process of transformation business ecosystem model into strategy.

1. Introduction

The activity of a modern organization takes place in conditions of rapid changes and uncertainty. Taking into account the sources of uncertainty make it possible to improve the management of organizational turbulence. The absence of a preformed path of activity in such conditions complicates the organization's path, creates risks and threats to future activities. Today, there are three main types of dynamism sources that an organization can use to develop in the face of change: technology, business model, and human resources. Each of these types corresponds to a certain limitation: for people – awareness of their needs and desires, for technologies – the possibility of developing and mastering them, for business models – viability and the ability to improve the existing business model. Organizations can manage uncertainty in different ways, focusing on one of these constraints: whether to focus on technological breakthroughs, as well as to study customers and their needs, or sometimes to improve existing business models. All this requires, on the one hand, considering what is happening behind the scenes outside the organization, and on the other hand, whether the organization can or sometimes wants to change its development strategy. Therefore, it is important to understand what challenges today cause the turbulence of the organization and how the organization can ensure its viability in such conditions, what management tools can be used to transform the strengths of the activity into opportunities for development, reducing threats and overcoming weaknesses. The business model itself encompasses the characteristics and properties inherent in the organization, which it transforms into the company's strategy and acts as a regulator of the viability of the strategy formed under the influence of modern challenges and development trends.

2. Literature review

The idea of connecting business and ecosystems dates back to the 1930s, when the English botanist Arthur Tansley coined the term ecosystem to describe a community of organisms interacting with each other and the environment, the components of which co-evolve and co-adapt to external changes. Hence, ecosystem was defined as the concept that in any closed system, its members must work together and around each other to keep the system stable, ideally optimizing the collective benefit [1]. In the natural world, we can observe how a balanced ecosystem benefits all participants, as well as how destructive an imbalance in an ecosystem can be, as we can observe the consequences of global warming. In turn, business strategist James Moore used the biological concept of an ecosystem to compare it to business and drew a parallel between companies operating in an increasingly interconnected world of commerce with a community of organizations that adapt and evolve to survive. Moore proposed to consider the company not as a single firm in the industry, but as a member of a business ecosystem whose members cover different industries [2]. Hence, the functioning of the business ecosystem model falls into the sphere of interaction between society and nature – the noosphere [3] – a concept introduced by W. I. Vernadsky and developed into the law of the noosphere – a provision formulated by the scientist about the transformation of the biosphere, according to which ”at the current level development of human civilization, it inevitably turns into the noosphere, that is, into the sphere where the human mind plays the most important role in the development of nature” [4], within which intelligent human activity becomes a determining factor of development [5]. By remaking nature and the environment, with his mind and the results of intellectual work, man changes the conditions of life on the planet, creating a noosphere, which, unlike the biosphere, does not have its own control mechanisms” [6].

The development of the idea of a business ecosystem fundamentally altering the key success factors for organizations, forcing them to think and act very differently regarding their strategies, business models, leadership, core capabilities, value creation and capture systems, and organizational models [6]. Therefore, taking into account the connection between the functioning of the environment and the activities of organizations, it is important to take into account that such interaction does not occur only between the environment and the organization itself, and the formed business ecosystem is considered as a set of legal entities and individuals of various fields and types of activity, “which functions for development of innovations and entrepreneurial activity by combining the efforts of various groups of stakeholders” [7]. In addition, the formation of the business ecosystem model, in addition to the connection “organization – ecosystem”, takes into account the trends of modern development, determined by the awareness of the need to take into account the conditions of sustainable development, the principles of the “knowledge economy”, the conditions of digitalization and the use of Business Intelligence NEO information and management systems, which allow better understand the goals and solve the problems of further development and implementation of these systems [8]. On the basis of research on the formation of the business ecosystem of an enterprise in the energy sector, it was concluded that this is an activity aimed at combining the efforts of interested parties, which, on the one hand, aim to achieve business goals, meet the needs for energy resources of various groups of consumers [9], and on the other hand, compliance with the conditions that ensure the balance of their activities for the realization of sustainable development goals [10] and the development of measures to maintain the ability of the business ecosystem to preserve its structure and functionality under the influence of external factors [11]. There were substantiated that oil and gas enterprises indicate a readiness for changes in instability of the functioning environment [12,13]. Thus, we define a business ecosystem as a network of organizations, including suppliers, distributors, customers, competitors, government agencies, etc., that participate in the supply of a specific product or service by competing, establishing cooperation, and establishing effective communications between business participants – ecosystems. The idea is that each member of the ecosystem affects others, constantly developing relationships in which each member must be flexible and adaptable to survive as in a biological ecosystem.

However, despite the fact that the idea of a business ecosystem has gained significant development, the issue of the transformation of the content, properties and requirements of the business ecosystem model into the enterprise development strategy has not been given enough attention. Based on the above, the purpose of the article is to characterize the relevance, structure and background of business ecosystem model formation and its implementation into enterprises' strategy taking into consideration the ways and tools forcing the transformation of mentioned model.

3. Methods

19 respondents who are stakeholders of the Ukrainian oil and gas production company, with whom a cooperation agreement has been concluded and who are interested in the results of joint activities, took part in the survey on the role of collaboration in transformational processes. The purpose of the survey was to find out how stakeholders understand the concept of "collaboration" and to determine their readiness for cooperation. The received answers are important for understanding directions and ways of improving interaction, strengthening mutual interest and participation of both the enterprise and its stakeholders in achieving joint results.

4. Results

Modern global energy development trends are determined by the need for energy resources and the problems of transition to low-carbon energy systems to ensure the sustainable development of both individual enterprises and countries and the world in general. Analytical reports predict that in the next 10 years the structure of energy consumption and their energy intensity will not change significantly, and consumption will increase by 2 units of Kj/person [14]. At the same time, experts and scientists note that the increase in the consumption of energy resources is accompanied by an increase in the emission of CO_2 into the environment. The Global Carbon Project estimates that global emissions of CO_2 will remain relatively high at 40.5 Gt CO_2 in 2022, but still below their 2019 peak of 40.9 Gt CO_2 [15]. Of the existing traditional types of energy resources, natural gas has the lowest emission volume of 0.2 kg/Kd CO_2, the largest – peat 0.38 kg/Kd CO_2 and wood 0.39 kg/Kd CO_2. [16]

We note that quantitative data of the business ecosystem development is important for informational support of strategic decisions in the ecosystem's era. The conducted research and the obtained results [17] confirm the relevance and positive dynamics of the creation of added value in various of ecosystems domains. In figure 1 the volumes and dynamics of the creation of added value in certain domains of ecosystems are presented for Europe, NAFTA and the world.

Figure 1. Volumes and dynamics of the creation of added value in certain domains of ecosystems for Europe, NAFTA, and the world [17].

As we cam see from the figure 1, all chosen ecosystem's domain has positive trends in creating of added value as well as in others, mentioned in the analysis [17]. In such conditions, taking into account the potential and capacities for the extraction of energy resources in Ukraine, as well as the need of energy security and energy independent, it is important to take into account the specified trends in the activities of oil and gas production enterprises. The desire to ensure sustainable and stable development of the energy sector led to the adoption of a number of documents that define the strategic directions of development, in particular, of energy enterprises. Modern strategy directions of energy sector development in Ukraine are represented by the following normative documents: Energy strategy of Ukraine for the period until 2035 "Security, energy efficiency, competitiveness", which creates prerequisites for combining business goals and goals of economic development with goals in the field of environmental protection [18]; Low-carbon development strategy of Ukraine until 2050 [19]; Law of Ukraine "On environmental impact assessment" [20], which gives the public the right to submit any comments, objections and proposals, which increases the level of its participation in the process of assessing the environmental impact of the planned activities of the management entity; the unfolding of the Russian-Ukrainian war, which forced a complete reconsideration of the issues of energy supply, energy efficiency and energy security.

Ukraine's accession to the EU and, accordingly, following the regulatory and legal context of integration requirements indicates the need to take into account their basic provisions in modern strategy directions of energy sector development. The national long-term strategies and the EU's strategy have to cover, with a perspective of at least 30 years [21] the next issues: total greenhouse gas emission reductions and enhancements of removals by sinks; emission reductions and enhancements of removals in individual sectors, including electricity, industry, transport, the heating and cooling and buildings sector, agriculture, waste and land use, land-use change and forestry; expected progress on transition to a low greenhouse gas emission economy, including greenhouse gas intensity, CO_2 intensity of gross domestic product, related estimates of long-term investment, and strategies for related research, development and innovation; to the extent feasible, expected socio-economic effect of the decarbonisation measures, including, inter alia, aspects related to macro-economic and social development, health risks and benefits and environmental protection; links to other national long-term objectives, planning and other policies and measures, and investment.

These trends and challenges are reflected in the development of energy companies and influence the formation of their development strategies. Building business models allows

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determining the criteria, types of activities and processes that support enterprises to achieve their goals and implement a development strategy. The formation of a business ecosystem model of an enterprise in the energy sector demand the unifying the efforts of interested parties. This, on the one hand, will lead to achieve business goals, meet the energy resource needs of various groups of consumers, and on the other hand, will observe conditions that ensure balance between the activities to implement strategic goals and the development of measures of maintaining the ability of the business ecosystem to support its structure and functionality under the influence of external factors, taking into account global development trends and energy development strategies. Thus, we associate the implementation of the strategic goals of the enterprise based on the coordination of business interests with the task of minimizing the negative impact on the environment, with the formation of a business ecosystem model that allows realizing the potential of the enterprise and, if necessary, strengthening it in order to create conditions for implementation enterprise strategy formed under the influence of internal and external environmental factors (figure 2).

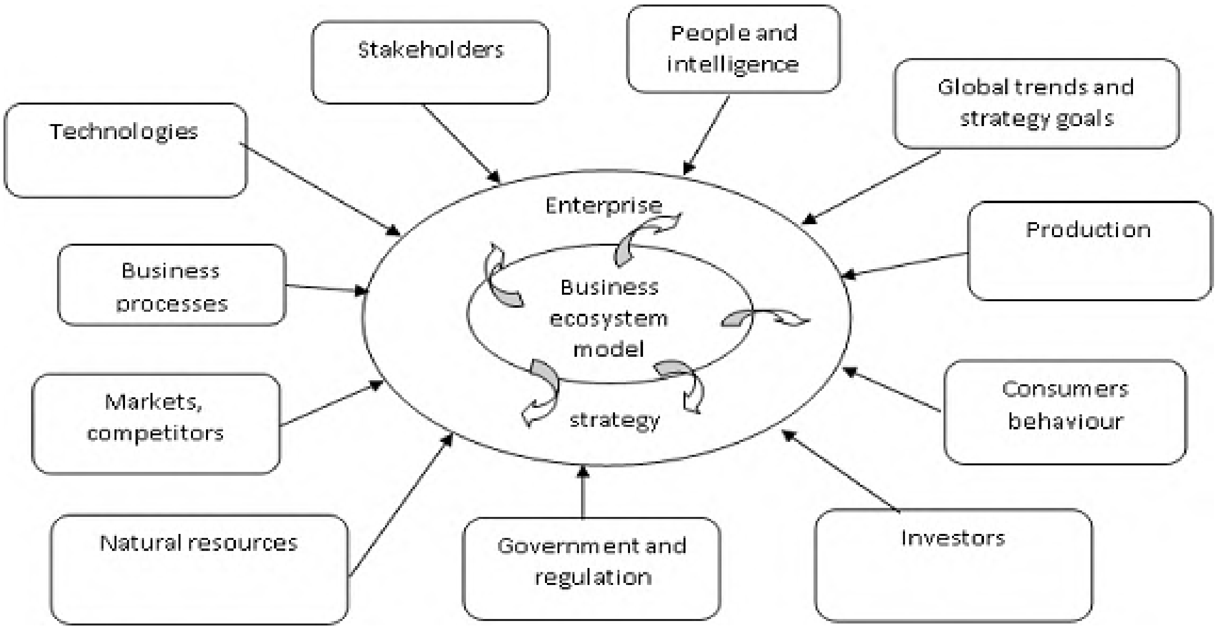

Figure 2. Determinates of enterprises strategy formation and it's connection with enterprise's business eco model.

In turn, the model is a tool for implementing the company's development strategy, takes into account the factors of the internal and external environment that influence the formation of the strategy and covers those components that integrate business processes, natural ecosystems and people involved in this integration process. An important task is the transformation of the model into a strategy as a consistent and systematic solution to the tasks of enterprise development based on the application of transformation tools, the choice of which depends on the selected type of transformation. Transformation processes involve the participation of stakeholders, collaboration with which is also important for transformations of the traditional orientation of energy companies' activities on economic results and business interests accounting the benefits of an ecosystem approach, which adds added value by reducing harm to the environment and people.

We note that the strategic goals of the enterprise must be harmonized with the strategic goals of the enterprise's environmental policy, within which the business model of the enterprise will function and, if necessary, be improved. The idea of a business ecosystem model proposed in this article involves the selection of spheres of activity, business processes, areas of activity that ensure the implementation of the company's tasks while simultaneously complying with the provisions of approved regulatory documents declaring the task of observing environmental policy and environmental responsibility [22].

The search for an integrated approach to the strategic management of a group of internal and external stakeholders at industry enterprises, taking into account the principle of balancing their interests with the highest utility for enterprises, is exactly in line with the idea of a business ecosystem. Achieving the expected results, organizations occupy the appropriate market share, form an image, develop a brand. At the same time, striving to satisfy the needs of consumers, companies use, in particular, natural resources that form the ecosystem of a certain territory. The ecosystem model is a natural environment that exists according to the principle of self-regulation and is aimed at creating conditions for the survival of all participants of this system and is regulated by the laws of nature. Therefore, in the content of the business ecosystem, we include the concept of a business structure that works using the principles of functioning of ecosystems, in particular, self-regulation to maintain its viability.

It should be emphasized that it is precisely for these reasons that in today's business world a company creates its own business ecosystem or invents a way to join an existing ecosystem, finding an advantage that does not currently exist in this ecosystem. Note that, like natural ecosystems, enterprises that are subjects of business ecosystems compete for survival, adapting to business conditions, and sometimes disappearing. The process of moving from the company's existing state to strategic goals occurs through transformation. We recognise business transformation as the process of fundamentally changes of systems, processes, people and technology across a whole business or business unit, to achieve measurable improvements in efficiency, effectiveness and stakeholder satisfaction. According to experts, the transformation process is based on a vision of the need for changes and a clear understanding of them, which is formalized through a portfolio-mix package, in particular, for the energy industry, it includes a low-carbon portfolio, green energy business; optimal portfolio of decarbonized hydrocarbons and green business. The implementation of measures within the list of promising types of activities is based and supported by value drivers such as environmental, social, governmental footprint; trust and confidence of stakeholders; balance between growth and financial flows. All this can be implemented through Business models formed for specific purposes: strategic partnership; low-carbon enterprise and equipment; ecosystem development.

Management practice involves three types of transformation, which depend on the company's readiness for changes, the environment in which the company operates, and management, which considers changes as a necessary condition for the organization's development, namely: evolution as a long-term, planned and well-executed gradual change in resource allocation and business areas; shift as a sudden strategic move that carries massive and abrupt changes to the business models and underlying value creation logic; shock is triggered by outside events or outside pressures that force the company to transform, or at least attempt to transform [23].

We offer to consider the experience of the Ukrainian energy company, which is engaged in gas extraction. The company implements and plans to expand measures that are provided in the field of main and supplementary activities and are aimed at reducing CO_2 emissions, waste management through the implementation of the concept of "green logistics", achieving energy efficiency and energy saving. New challenges that appear as a result of man-made impact on the environment pose new challenges to enterprises of the oil and gas complex. When engaged in the main activity of extraction, production, supply, storage and distribution of energy resources, they must take into account the requirement to carry out their activities with the least harm to the environment, realizing the need for the development of alternative sources of energy resources for the relevant sectors of the economy and various spheres of social life.

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Table 1. Strategic goals and outcomes of business ecosystem model at the oil and gas production company.

№	Elements of business ecosystem model	The main idea	Outcomes
1	Decarbonisation	Decarbonization is the term used for removal or reduction of carbon dioxide (CO_2) output into the atmosphere	Emission reduction goals to mitigate climate change. Decreasing of payments on environment's pollution competitive advantages.
2	Waste management	The aim of waste management is to reduce the dangerous effects of waste on the environment and human health.	Saving money on what you buy. Cutting your waste disposal costs. Meeting your environmental obligations. Finding new sources of revenue.
3	Energy efficiency and energy saving	Energy efficiency and energy saving mean using less energy to perform the same task – that is, eliminating energy waste.	Reducing greenhouse gas emissions, reducing demand for energy imports, and lowering the costs on a household and economy-wide level.

We suggest considering the strategic goals and the results of their achievement on the example of a gas production company table 1. Here is the description of business ecosystem model elements:

1. Decarbonisation transformation tools: related to the reduction of gas emissions during its extraction. One of the possible ways to solve this problem is capture of associated gases during extraction with their further use. The format of the business ecosystem model contains processes that will allow the reduction of CO_2 emissions into the atmosphere due to optimal route planning; reduction of idle time in traffic jams and reduction of fuel consumption, cargo consolidation and use of rail transport.
2. Waste management transformation tools: the company links with Implementation in the business ecosystem model the "green logistics" system in order to establish a system for monitoring the volumes of waste processing and consumption. This logistics system is formed in certain stages according to its functional structure. The first stage is the stage of supply, which is characterized by the formation of a logistics chain, which includes the following functions: collection, transportation and storage of secondary raw materials. The second stage is the sorting stage, which includes the identification, certification and sorting of secondary raw materials and waste and determines their qualitative and quantitative composition, forms a data sheet on waste, conducts an ecological and economic analysis of waste, as a result of which it will be determined whether the given waste is suitable for processing. The next stage – the implementation stage – takes place after waste processing and their promotion to the market as a product, which involves inventory logistics and warehouse logistics. If, after the analysis, it was determined that the waste was unsuitable for processing, the disposal stage is carried out, which includes the development of disposal systems, taking into account the types of waste and the characteristics of the region [24].
3. Energy efficiency and energy saving transformation tools: are implemented through processes that consider thermal insulation of industrial premises as a relatively cheap way

to increase their heat output, thus achieving a reduction in energy costs for heating and reducing the overall load on the environment by reducing the energy intensity of this type of activity; use of alternative energy sources to ensure energy supply of industrial premises.

Taking into account the necessary ecological changes [25] to the business model requires consideration of the preconditions for their transformation into a development strategy, followed by their implementation through the same model. Consideration of issues of collaboration and communications acquires special importance in the process of transformations, since the achievement of strategic goals involves the involvement of all interested participants and the achievement of understanding and interaction in the process of implementing the model for achieving development strategies. The transformation of the model into an enterprise strategy based on the approval of technical measures with the use of appropriate technologies, is accompanied by the study and application of modern management technologies, developing a policy of collaboration and improving communications.

The questionnaire results on collaboration perception by stakeholders could be used in transformation. And the main issues necessary to align with in the collaboration are inherited from the current perception of people, representing the enterprises during the realization of business contracts. And getting results can help to create an environment and conditions for collaboration, namely: 61% of representatives tend to require responsibility in the process of collaboration (figure 3). Team work is leading when interacting with stakeholders. At the same time, 11% of respondents do not have a clear strategy of interaction with stakeholders (figure 4).

On the question how often do you collaborate with stakeholders the most answers indicated the condition when it needed (55%), 11% of respondents indicated the need according the one tine concluded agreement, and 17% of them constantly support relationships with stakeholders. Thus, we can conclude that collaboration isn't considers as continues process but mostly as once time action, and this require appropriate policy of collaboration formation (figure 5).

Evaluating trust in cooperation with other enterprises, it was determined that 50% of respondents are inclined to test previous experience (figure 6). Thus, the results of the survey allow us to identify issues and directions for the future development of the prerequisites for transformation, such as the willingness and ability of stakeholders to support changes and facilitate their implementation.

To succeed in the transformation process, a system of communication needs to be established. Meaning, that the key people/groups and their communication channels must be taken into account – any system consists of objects and relations between them [26]. Moreover, from the perspective of the information theory the people become the nodes of the system and

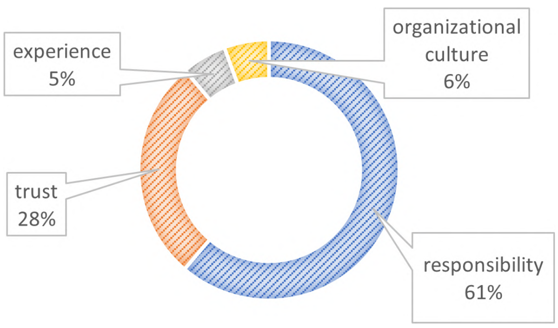

Figure 3. Answers on question "What collaboration does require first of all?".

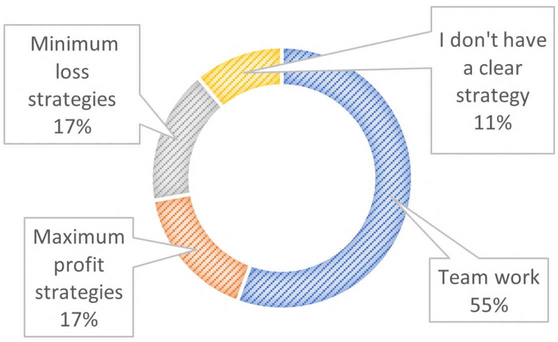

Figure 4. Answers on question "When interacting with stakeholders, what do you adhere to the strategy?".

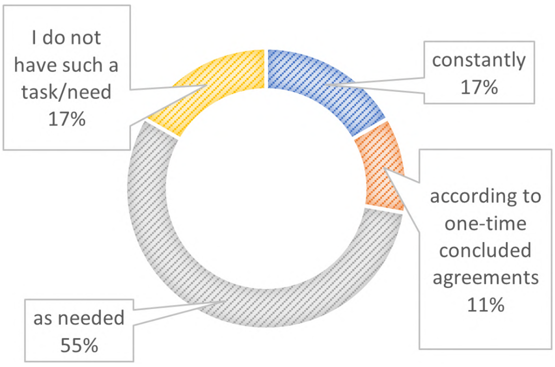

Figure 5. Answers on question "How often do you have to collaborate with stakeholders?".

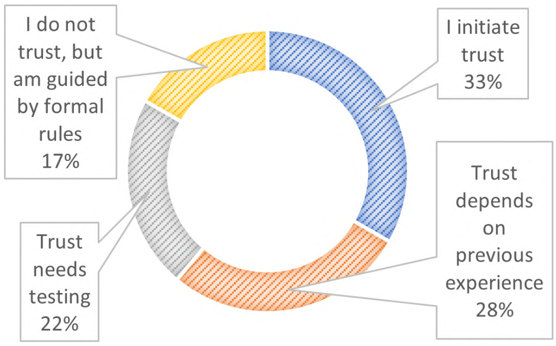

Figure 6. Answers on question "Assess the trust in representatives of other enterprises you work with".

how they communicate becomes its connections between those nodes. So, we must design a communication system, which means creating an effective implementation of the information theory. The most important aspect of creating a communication system is to understand the communication factors that directly affect the priorities and overall behaviour of the system created [27]. The following list defines the most important factors for information system design on improvement: number of nodes; number of connections; information distribution and security; transmission speed and bandwidth; transmission loss; transmission complexity; transmission integration; transmission parallelism; transmission scaling and flexibility.

The complexity of transmission (protocols and tools) is the fifth factor. We would like to present the example of such means at table 4. Even though we design how the nodes are connected, it's impossible to strictly set all of the connections, because the nodes of transmission are people and humans are prone to bringing their features of communication with other humans. So, we should provide the templates of connections, not the exact solutions, and the strict protocols of what's not allowed instead of how to implement the given template – to avoid alienation (a person's feeling of disconnection from a group) and give people the freedom to choose what makes sense in their particular context and situation instead of trying to foresee all potential cases.

Table 2. Communication means (technologies) for transformation process.

Elements of business ecosystem model	Transformation types		
	Shock (Extraordinary events)	Shift (Innovations)	Evolution (Sustainable development)
Decarbonization Waste management Energy efficiency and saving	Mass media Public control Press conferences	Start-up conferences Niche markets Local communities Investment pitching	Strategy meetings Road maps Programs Public Conferences

Taking into account everything said above, the hierarchy of the information transmission factors must be considered due to its direct impact on the contradiction between the factors (i.e. the higher integration the system has, the better its scalability). For example, the successful realization of the complexity factor requires a corresponding material-technical base. Another example is the monitoring of the created system, which provides the evaluation of the overall communication effectiveness. It's crucial to understand that the system runs with the speed of the slowest connection between nodes. So, each node should strive for both being effective at encoding, interpreting, and decoding the information transmitted. In other words, interpretation is the cornerstone of any system where people are the central node, so we must motivate them to explain themselves and understand others to their best ability. Also, way too often there are redundant connections that don't bring any benefits but only slow down the overall bandwidth of communication, so minimization of the connections is another way of optimizing the system structure. It's important to highlight that minimization must be done extra carefully because it leads to an increase in the number of connections each node has, which in turn increases its relative importance – this directly affects how secured the given node must be.

5. Discussion

Today, business practice has formed a significant list of modern business models that use approaches and methods of organizing and managing activities allowing the enterprise to adapt its business processes to the environment due to the modern challenges and development trends. There is a practice of forming business models of leading companies in the world, which ensure their success and competitiveness. Examples of such companies are Amazon, Google, Apple, FedEx, Southwest, Walmart, McDonald's, IKEA, Enterprise, eBay, Dell Computers, Starbucks, Skype, Groupon [28]. We note that the success of the enterprise is ensured by those business models that are based on modern technologies, are oriented towards the consumer, as well as are able to develop human resources, and ultimately provide the enterprise with the uniqueness that allows the realization of strategic goals formed on the basis of a perspective vision of the company role and value. Hence, the formation of the business ecosystem model takes place on the basis of the improvement of existing business models, their reengineering as required, and the mandatory condition of functioning includes the principle of the existence of the ecosystem as the ability to self-regulate and recover [29].

The proposed concept of the business ecosystem model transformation into an enterprise development strategy takes into account the peculiarities of its activity, in particular, for this publication, it is the field of oil and gas production. Actually, the transformation takes place by proposing measures in the areas of activity that correspond to the potential strategic goals of the activities of industry enterprises, which are determined by the prospects of the industry. Note that presented in figure 7 stages of transformation of the business ecosystem model are debatable, because it may appear that the business ecosystem model includes strategy as one of the components of the business model.

However, the enterprise defines a business model that will allow the implementation of a strategy aimed at solving strategic tasks. That is, the processes of the business model describe how the enterprise turns strategic goals into profit, and the strategy focuses on creating opportunities to function in a competitive environment and implement tasks, in particular global development. Despite the emphasis on the specifics of the oil and gas industry, the concept of transformation of the business ecosystem model into an enterprise development strategy has a generalized nature and can be used for enterprises of other industries, however, taking into account that the central point of the transformations is the orientation to the principle of balanced functioning of the business ecosystem derivatives. In addition, such an approach to the orientation of the business model on environmental problems is relevant in the conditions of the post-war recovery of the Ukrainian economy, namely the energy sector. Reconstruction should involve not only the restoration of the physical condition, but also a fundamental rethinking of methods that will allow meeting energy needs with the least harm to people and the environment.

Further research is needed to examine whether the strategies available in enterprises take into account the prospects and trends of the development of the industry based on the consideration

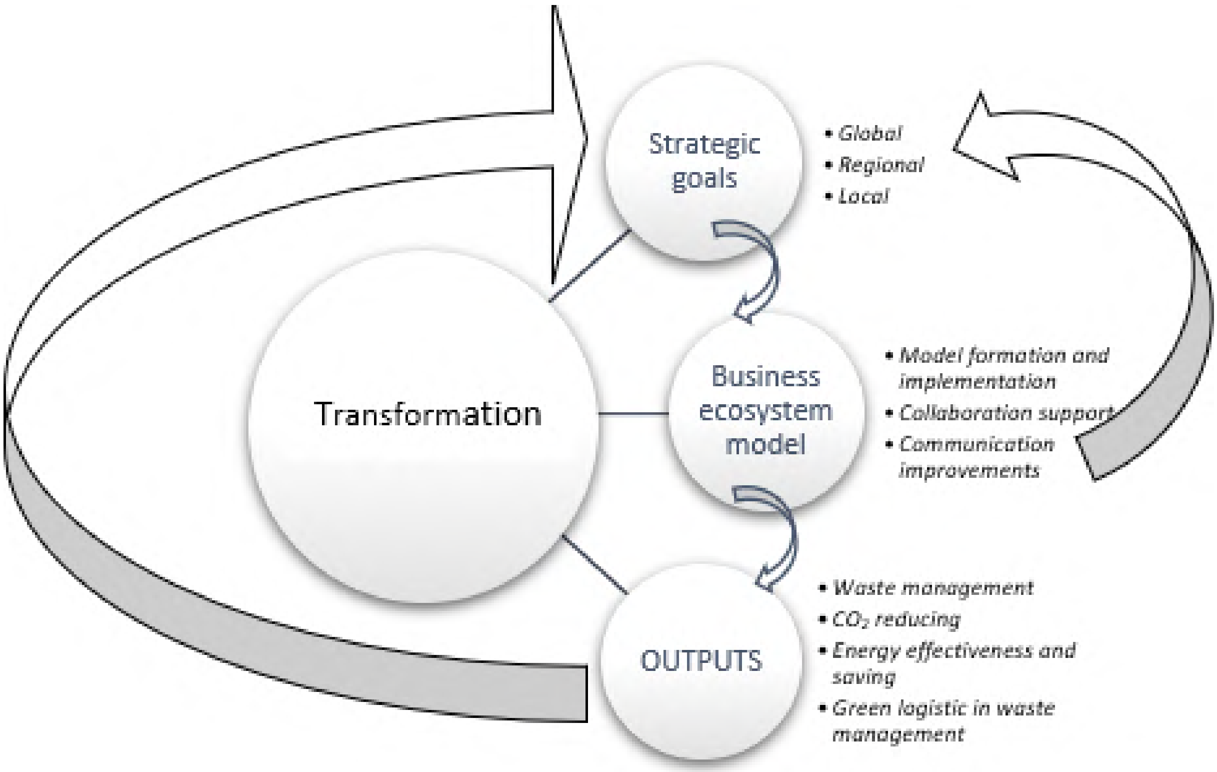

Figure 7. Stages of transformation of the business ecosystem into the strategy of the oil and gas production enterprise.

of international and national legislation and standards, in order to assess the extent to which existing business models are able to realize strategic development goals.

6. Conclusion

The formation of a business ecosystem model of an enterprise in the energy sector is an activity aimed at combining the efforts of interested parties, which, on the one hand, aim to achieve business goals, meet the energy resource needs of various groups of consumers, and on the other hand, comply with conditions that ensure the balance of their activities for the realization of sustainable development goals and the development of measures to maintain the ability of the business ecosystem to preserve its structure and functionality under the influence of external factors, taking into account global development trends and energy development strategies. The model is a tool for the implementation of the energy company's development strategy, takes into account factors of the external environment that influence the formation of the strategy and includes those components that integrate business processes, natural ecosystems and people involved in this integration process.

An important task for enterprises striving to adopt their activity to the global, national, and local trends is the transformation of the model into a strategy as a consistent and systematic solution to the tasks of enterprise development based on the application of transformation tools, the choice of which depends on the selected type of transformation: emergency, innovative and evolutionary. Depend on the transformation type the different approaches could be decided to adopt an enterprise to the challenges and trends. Transformation processes involve the participation of stakeholders, cooperation with which is also important for transformations of the traditional orientation of energy companies' activities on economic results and business interests, considering the benefits of an ecosystem approach, which makes additional value to the business by reducing harm to the environment and people.

Consideration of issues of cooperation and communication acquires special attention in the process of transformations, since the achievement of strategic goals involves the interested of relevant participants and lead to more understanding and interaction due to the collaboration in the process of implementing a business ecosystem model for achieving developed strategies.

The concept of the business ecosystem transformation into the strategy of an oil and gas production company proposed in the article includes and structures the main elements of the functioning of the model, which are related to the company's activities and stem from the strategic goals of global trends, and also include specific characteristics that distinguish the business ecosystem model from traditional business models.

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Analysis of the motivational profile of personnel directed at achieving sustainable development of the enterprise

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Analysis of the motivational profile of personnel directed at achieving sustainable development of the enterprise

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Abstract. The article is dedicated to the study of motivational profiles of employees, identifying dominant motives in conditions of war and uncertainty to develop the proper tools for directing personnel behavior toward reaching the goals of sustainable development. The study was conducted at bakery enterprises in the Sumy region of Ukraine in 2023. The methodological basis of the study is the author's approach to structuring motives, which adapts the classic Martin and Ritchie methodology, sociological research methods (questionnaires, focus group surveys) and statistical analysis to the current conditions in Ukraine. As a result, the hypothesis regarding the dependency of the structure of motives (the image of the motivational profile) of employees on their position within organization and the nature of their work was confirmed. It was shown that management pays little attention to the development of motives directed at achieving sustainable development; at the same time, the very nature of work can serve as the basis for the behavior focused on sustainable development goals (for example, the value of work results for society). At the same time, it is apparent that the war changed the structure of motives: safety in the workplace instead of being just important becomes one of the key motives; the motives of social participation and psychological well-being of personnel acquired a greater weight. Unfortunately, though environmental behavior is understood and accepted as important in the structure of motives of employees, in the real motivational profiles it takes an average level, which indicates the impact of stress and war on the priorities as well as minimal efforts of company management in the development of "environmentally responsible" personnel. The obtained data became the foundation for the recommendations offered to improve staff motivation that include components relevant to the current situation of uncertainty and risks and are aimed at achieving sustainable development goals.

1. Introduction

The modern world is so dynamic and subjected to the influence of social engineering that all business processes have become dependent on non-economic determinants. Thus, reputation can often increase a company's rating overnight or turn the company into a loser [1]. Therefore, the quality of a company's human capital determines how successful and thriving it will be in the world of new social interests. These interests include the goals of sustainable development. According to the studies [2,3], the interest of company managers and ordinary employees in the implementation of sustainable development goals is rising constantly. In addition, in recruitment, one of the criteria for choosing a workplace by a candidate is the implementation of social projects and the company's adherence to sustainable development goals (especially in terms of the green agenda) [4]. The modern financial and economic world is characterized by a reorientation toward sustainable development goals, so considering the development of an enterprise cannot be imagined on a different plane than personnel management based on the principles of green management and corporate social responsibility.

The pivot point of the concept of "green" personnel management is and should be the value structure of human capital. For example, if greater attention is paid to the environmental component during the assessment of the methods of personnel management, this means that achieving the corresponding goals requires that the company's personnel and its top management not only have the necessary competencies but also have internal motivation to achieve such goals. Simply put, it is incorrect to claim that the company is implementing sustainable development goals without the existence of interests and motives among employees toward such goals. Based on the conclusions of scientists who developed a model of business ethics [5], issues of corporate social responsibility, especially in terms of environmental management of an enterprise, are decisive in strategic management. In addition, creating a sustainable business is impossible without the existence of a developed sense of social responsibility, which is defined as the desire to materialize internal and external motives. At the same time, internal motives include concern for nature or the good of society, and external motives include meeting the needs of customers and the willingness to achieve the well-being of employees [6].

In influencing employee behavior through motivation management, companies are often focused on the principles outlined in green HR management, which include developing talent, providing access to new ideas and resources that can help employees become more creative and innovative [7], and fostering well-being, productive social and labor relations, and high-quality communication. Traditional models and methods that take into account the age structure of personnel and the life cycle of the company's development are equally important in motivation directed at achieving sustainable development of a company [8]. At the same time, the very turbulence of the political and socio-economic environment requires constant modification of approaches and tools for motivating personnel, which invariably entails an analysis of the motivational profiles of personnel.

2. Literature review

Personnel management founded on the principles of corporate social responsibility includes all classical processes – from personnel selection and assessment to labor organization, as well as modern ones – digitalization and talent development. Moreover, all processes are in one way or another connected with motivational practices. Considering the increase in the factors of instability of the external situation and changes in personnel values [9], the most acceptable construct for motivation is the "ability-motivation-opportunities" model [10], because it takes into account the values of personnel as much as possible and demonstrates the relationship between motivation for development and behavior of employees, results of their work, and, consequently, increasing productivity of labor, and improving other economic indicators of the company's activities that depend on human capital. This logic is very similar to "green" personnel management. In particular, the goal of motivation will be to achieve sustainable business development, including environmental, by changing employee behavior through additional training.

It is worth noting that motivations are not constant and vary during lifetime with the changes in life conditions. The ongoing war in Ukraine has a catastrophic impact on the economy, human lives, and overall worldview. The priorities and motives are also visibly changing: the motives of safety become paramount [11]. Also, in the innovation sector, the wartime conditions bring forward motives of participating in the work toward the victory [12]. However, low wages and minimal understanding of the importance of work reduce enthusiasm and motivation of employees [13].

Besides, rising uncertainty and risks due to wars, pandemics, and natural as well as man-made disasters are increasingly pushing stakeholders toward the task of ensuring the sustainable development of the company. As Casey and Sieber note, the sustainable development of a company becomes the goal not only of the company itself but also of its employees [14]. Personnel management and motivation (as a component) in the context of sustainable development assumes that both management and all employees are interested in achieving goals and are therefore involved in solving social and environmental problems. Thus, motivation should be focused on a triple result: economic, social, and environmental, which is impossible without influencing the development of a certain motivational profile of an employee. At the same time, the values and interests of each employee must be correlated (harmonized) as much as possible with the goals and strategy of the company. This fully meets the principles of social responsibility and will be implemented through social projects of companies [15].

On the other hand, motivation focused on achieving sustainable development goals can be viewed through the prism of stakeholder (primarily staff) satisfaction. For example, if the content of the work is well-defined and meets the goals and interests of the employee, including social and environmental, then the employee's motivation will be higher. As noted in the study by Shafaei, Nejati and Yusoff [16], such aspects of motivation as involvement, the opportunity for self-realization and participation in social projects, fairness in the appreciation of work, compliance of working conditions with "green" standards, and satisfaction with the content of labor are the basis of "green" personnel management, as one of the goals of sustainable development.. However, the impact of the stress on the motivation of the personnel also becomes evident: the external stress factors (war, devastation) make employees to "accumulate" fatigue and lose productivity of labor [17]. It indicates the difficulties that can arise in motivating people toward reaching the goals of sustainable development.

As we can see, the issue of motivation is very relevant for the sustainable development of a company. However, effective motivation can be achieved by taking into account the values of employees in the selection of motivation tools, i.e. their motivational profile. For the first time, the term "motivational profile" was found in the work by Ritchie and Martin [18], which they understand as individual stimulating factors. Publications devoted to the study of the structure of the motivational profile are most numerous in the pedagogy and psychology of students [19–22], however, there are studies of the motivational profile of workers in various fields of economic activity [23]. In general, all researchers agree that the motivational profile of an employee reflects the dominant motives in work activity and includes the most relevant goals for him. Therefore, an analysis of the motivational profile of the staff will allow us to assess the coincidence of the goals of all employees and the company, the potential and possibilities of their involvement in the implementation of social projects, and other sustainable development goals.

3. Methodology and objectives of the study

The purpose of this research is to study the motivational profiles of personnel to identify dominant motives and, based on this, propose directions for motivating employees of the studied enterprises that contribute to their sustainable development; identify or refute the hypothesis regarding the existence of differences in the structure of motives of different categories of personnel.

Based on the goal, various methods for constructing and analyzing a person's motivational profile were analyzed. The method used by Ritchie and Martin [18] was modified to suit the task of identifying motivation for the sustainable development of an enterprise, the parameters were also semantically clarified. Thus, "acknowledging work results" was redefined as "fairness of labor assessment" because employees would rather know how their work is evaluated by all stakeholders than know it was just acknowledged as existing. The term "Self-improvement" was defined as "Development and training" because this way personnel, as shown by answers of experts, would easier understand the nature and ways of self-improvement. Besides, the term "Interesting and useful work" was clarified and the emphasis was placed on usefulness for society rather than for the employee. Also, there were additions to assess social participation (charity, involvement in social projects) and an environmental component; social contacts and relationships were identified as psychological well-being and social interaction. Thus, the classical methodology has undergone some changes that adapted it to the semantic understanding of the terminology by personnel and expanded the assessment categories setting the focus on motivating personnel to achieve sustainable development goals.

A questionnaire developed according to this method was created in Google Forms, which included questions on self-assessment of the following motives: High earnings and material incentives; Physical working conditions; Structuring (need to establish clear rules for work performance, availability of feedback); Social contacts (the need to communicate with many people); Relationships (the need to form long-term close relationships); Recognition; Striving for achievements; Power and influence; Diversity and change; Creativity; Development and training; Interesting and useful work. The selected scale for assessing each value factor is presented in the range from 0 to 12 points. In this case, 0 is a complete lack of interest in the named factor, and 12 is its maximum representation (impact on behavior), the employee's interest. According to the logic of the study, the employee intuitively determines the characteristic level of one or another proposed factor-motive. Transformation of the results assumes the following scale for assessing motivation: 10.1-12 – Very highly motivated; 8.1-10 – Highly motivated; 6.1-8 – Rather motivated than not motivated; 4.1-6 – Rather unmotivated than motivated; 2.1-4 – Low motivation; less than 2.1 – Lack of motivation or negative motivation.

The study was carried out in March 2023. Unfortunately, 8 people filled out the questionnaire incorrectly. This indicates the complexity of the study for employees. Therefore, to clarify some results and identify links with the goals of sustainable development, the following was conducted: 1) an express survey in a focus group (10 percent of the sample corresponding to the structure of enterprise personnel and participants in the first survey) of enterprises participating in the study in June 2023, which made it possible to formulate the goals of sustainable development for these enterprises; 2) a sociological study in September 2023 among the same respondents (previously, all participants were sent a letter explaining how to fill out the Google form) to determine the link between staff motivations and sustainable development goals.

The survey was attended by 22.5 percent of the general group of bakery enterprise workers in the Sumy region of Ukraine. According to the structure, the respondents are represented by managers (15.6 percent of the entire group of respondents), managers and specialists (22.0 percent of the entire group of respondents), as well as workers (62.4 percent of all respondents). In this study, gender and age aspects were not detailed, because The personnel structure of companies remains unchanged for a long time (there is practically no staff turnover).

4. Analysis of the motivational profile of bakery enterprise personnel and defining priorities in their motivation

The results of the first survey made it possible to determine the significance and integral score of the motives that are inherent in employees of bakery enterprises (table 1).

Table 1. Qualitative evaluations (averaged) of significance and satisfaction by factors for respondents by personnel categories.

Indicator	Factors											
	High salary	Working conditions	Content of work	Social contacts	Psychological well-being	Recognition	Result driven	Power	Changes, innovations	Creativity and ingenuity	Self-refinement	Useful, interesting work
Workers												
Significance of the factor	1	0.9	0.5	0.8	0.8	0.8	0.6	0.2	0.3	0.3	0.6	0.7
Satisfaction level	0.3	0.8	1	0.7	0.7	0.6	0.5	0.6	0.8	0.7	0.7	0.8
Integral meaning of the motive	0.3	0.72	0.5	0.56	0.56	0.48	0.3	0.12	0.24	0.21	0.42	0.56
Specialists												
Significance of the factor	0.89	0.76	0.21	0.71	0.94	0.86	0.87	0.84	0.74	0.63	0.70	0.70
Satisfaction level	0.33	0.89	0.89	0.44	0.21	0.20	0.21	0.69	0.69	0.63	0.64	0.70
Integral meaning of the motive	0.29	0.67	0.19	0.32	0.20	0.17	0.19	0.58	0.51	0.40	0.45	0.49
Managers												
Significance of the factor	0.8	0.3	0.5	0.86	0.84	0.94	0.88	0.78	0.68	0.78	0.88	0.8
Satisfaction level	0.28	0.94	0.9	0.84	0.82	0.46	0.4	0.92	0.52	0.56	0.68	0.6
Integral meaning of the motive	0.224	0.282	0.45	0.72	0.69	0.43	0.35	0.718	0.354	0.437	0.6	0.48

The data in table 1 indicates the following. Firstly, motivation is shown as the sum of integral assessments of motives (according to the degree of its influence and significance):

- for the worker, it shows a value of 4.97, which indicates a fairly low motivation for this category of personnel in general;
- for specialists, it is at the level of 4.46, which indicates low motivation for this category of personnel;
- for managers, the value is 5.735, which demonstrates the average level of motivation and the existence of possible reserves for improving the interest of employees in improving work results.

Secondly, for certain motives, radically different assessments of motives can be seen, which is explained by differences in people's interests. Thus, the motive of "power" has the maximum significance for managers, but the least significance for employees; and the motive of "working conditions," on the contrary, is more important for workers than for managers.

Looking in more detail the resulting motivational profiles of workers (figure 1), specialists (figure 2), and managers (figure 3), the conclusions about the presence of differences in the perception of motives by workers and specialists and managers become obvious; the evident existence of factors that are inherent in the motivation system of enterprises, but do not influence the degree of motivation, and some reserves for improving motivation. In figure 1 1 – High salary; 2 – Working conditions (safety); 3 – The content of the work; 4 – Social contacts; 5 – Psychological well-being; 6 – Recognition; 7 – Result driven; 8 – Power; 9 – Changes, innovations; 10 – Creativity and ingenuity; 12 – Self-refinement; 13 – Useful, interesting work.

Thus, for workers (figure 1), the obvious priority is material well-being and working conditions. At the same time, they acutely feel the little appreciation of their work on the part of management, although there is an understanding of the value of their work on the part of the employees. At the same time, despite the motive "material support (wages)" being prioritized, workers still are not satisfied with its level. While motives related to innovation, creativity and power did not become a priority, therefore workers were satisfied sufficiently with these criteria. The motives of social interaction and psychological support are also important for workers, but the level of satisfaction with them is not high enough, i.e. workers feel a certain discomfort, especially in terms of psychological well-being and assistance, which they expect from management. Therefore, special attention must be paid to non-material motivation of workers. It is important to note that workers are well aware of the social usefulness of their work, which suggests that they are interested in the sustainable development of the enterprise.

It is typical for specialists (figure 2) to focus their motivation on social, psychological, and material factors of well-being. However, employees feel dissatisfaction with their work and its appreciation. They have motivation for development, positively assess the value of work, and the opportunity to participate in innovations, etc. In general, this profile indicates that enterprises have chosen the wrong priorities to motivate this category of employees. Without understanding or seeing a fair recognition of work, such employees are more likely to demonstrate interest than to make efforts to change the situation. The obtained data show that specialists are the least motivated group (the most negative factor is misunderstanding of the work content). One of the reasons for this is the psychological fatigue brought by uncertainties in life and work because of the war and poor management. According to the

		Square II					Square III				
Motivation of needs	1			1							
	0.9								**2**		
	0.8						**5, 6**	**4**			
	0.7								**12**		
	0.6					7		**11**			
	0.5										
	0.4										
	0.3							10	9		
	0.2						8				
	0.1										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
		Square I					Square IV				
		Satisfaction with the defined needs									

Figure 1. Structure of a worker's motivational profile.

				Square II					Square III		
Motivation of needs	1										
	0.9		5, 6, 7	1							
	0.8							**8**		**2**	
	0.7				4			**9, 12**			
	0.6						**10, 11**				
	0.5										
	0.4										
	0.3										
	0.2									3	
	0.1										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
				Square I					Square I V		
						Satisfaction with the defined needs					

Figure 2. Structure of a specialist's motivational profile.

answers, the managers saying that "don't ask for better pay as there are plenty people outside" do not help to motivate employees for higher productivity. Thus, motivating specialists and workers require more attention toward psychological well-being, assistance and better material support not only from their employers but also from the government.

				Square II					Square III		
Motivation of needs	1										
	0.9					6		**11**			
	0.8			1	7		**10, 12**		**4, 5**	**8**	
	0.7										
	0.6					9					
	0.5									3	
	0.4										
	0.3									2	
	0.2										
	0.1										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
				Square I					Square I V		
						Satisfaction with the defined needs					

Figure 3. Structure of a manager's motivational profile.

The motivational profile of managers (figure 3) shows high motivation for development and recognition of work, however, not understanding the meaning of social capital and the importance of psychological well-being can have a bad impact. Formally, this structure says that managers are sufficiently motivated and remain loyal to the enterprise, however, they are not showing their full potential. Material means of motivation are the least satisfying for managers, and they believe that their work is undervalued. It is noted that in conditions of ongoing war managers are less inclined to innovate although the need to make creative decisions is quite high (and they are aware of this). Managers realize the value of the work of their enterprise and are motivated to work there, which is the positive result, however, motives of achieving power still are their priority. The risks to personal safety negatively affects motivation (since managers are responsible not only for personal safety but also for the safety of all employees, when they can't ensure complete safety they face the dilemma which reduces their motivation; they "transfer" responsibility to the authorities). Thus, managers are quite motivated to solve operational problems but hardly consider achievement of bigger goals in their work.

The results of express surveys in a focus group made it possible to correlate the goals of sustainable development and the motives of employees. Thus, for managers and specialists, sustainable development was a condition of the enterprise when material well-being is beyond doubt, and at the same time, the enterprise has no debts, complies with environmental requirements, participates in social projects (for example, helping the poor, pensioners, orphans, etc.), and ensures a sufficient level of safety in the workplace. Workers understand the achievement of sustainable development goals as the social significance of their work – value for the entire population, arrangement of high labor safety, and social participation (involvement in the lives of employees and their families, assistance to hospitals

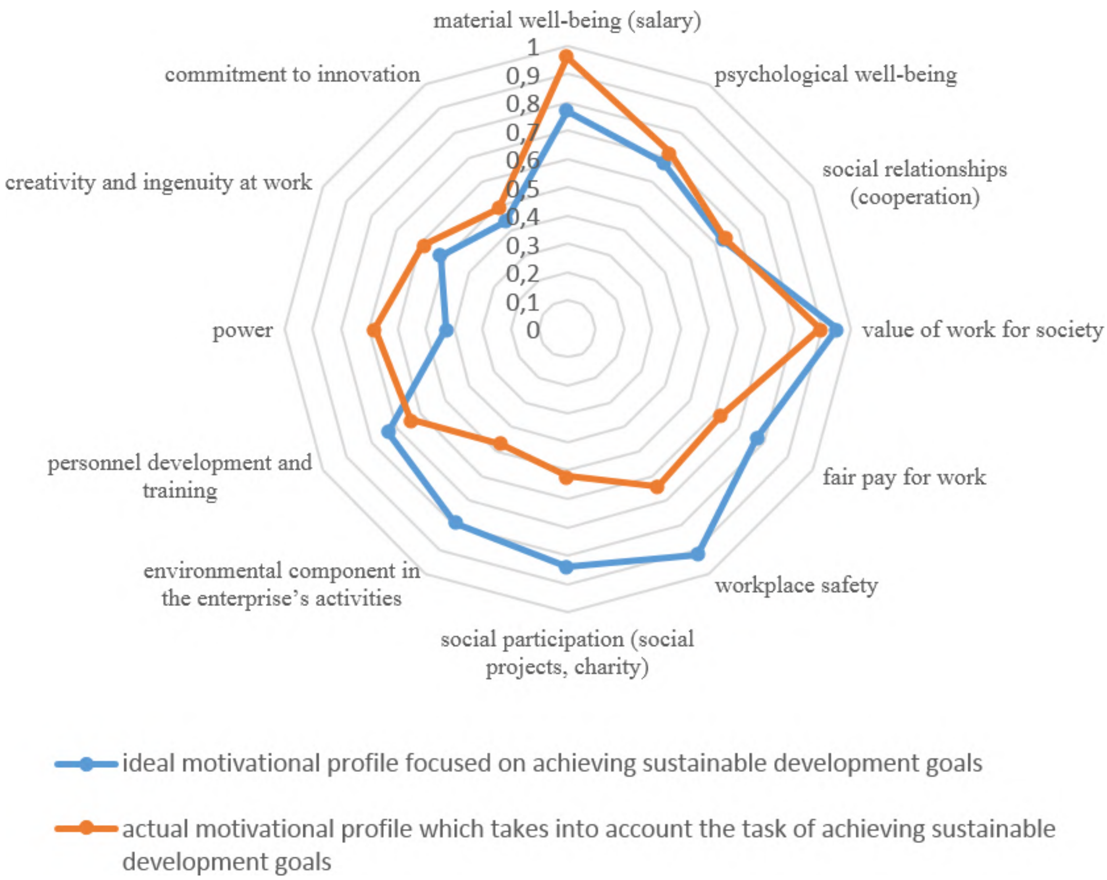

Figure 4. "Ideal" and actual motivational profile of an employee of bakery enterprises (average value), which takes into account the task of achieving sustainable development goals.

and boarding schools). Thus, the logical scheme of compliance of the motivational profile with the goals of sustainable development should include such motives as labor safety, mutual assistance, social participation, and material and psychological well-being.

The second survey, taking into account the updated and more correct formulation of motives designed for the sustainable development goals, showed that there is a difference between the "ideal", required motivational profile (which contributes to the achievement of sustainable development goals) and the actual one, which indicates that personal interests and everyone's vision do not always coincide with the efforts that need to be made to achieve results (figure 4). At the same time, a clear imbalance is observed in the motives of safety, social participation, development and fair recognition of work.

Based on the data obtained (figure 4), the offered model of personnel motivation must necessarily include the following components:

- decent level of remuneration;
- safety in the workplace (shelters, taking into account working conditions when setting work and rest periods, workwear, water, etc.) ;
- recognition of work, bonuses for work results;
- favorable socio-psychological climate ;
- involvement in social projects;
- training, including environmental behavior.

Thus, motivating the staff of bakery enterprises in the Sumy region of Ukraine involves carrying out activities directed at the development of sustainable motives that reflect "green" management, socially responsible behavior, and involvement in the social life of both the enterprise and society.

5. Conclusions and discussion

The scientific and practical values of the current research are the results of the approbation of the developed methods on the analyses of motives that serve the attainment of the behavior directed toward achieving the goals of sustainable development; adapting the methods of studying motivations of personnel to the current conditions in Ukraine and Ukrainian worldview, which would allow redefining personnel motivation and development goals. The hypothesis regarding the dependency of the structure of motivational profiles of employees on their position within organization and the nature of their work was confirmed.

To summarize, it should be noted that the majority of employees of bakery enterprises in the Sumy region of Ukraine have a very vague idea of sustainable development. Therefore, researching this subject required preliminary educational work. The data obtained indicate that employees have motives that directly correlate with those that contribute to the achievement of sustainable development goals, for example, the "work recognition" motive. Employees also agree that the motives for social participation and environmental behavior (for both employees and the enterprise) are very important for achieving sustainable development goals. However, taking into account dissatisfaction with the level of remuneration (level of material well-being and job recognition), the priority of these motives is significantly lower than the potential ("ideal" motivational profile).

In a certain way, such differences between the "ideal" and the actual motivational profile are justified by negative external factors – the risks associated with military operations. At the same time, traditional motives (wages) were and remain, regardless of external factors, the leading motives for the majority of personnel, especially workers. The current situation has rather increased the priority (brought it to dominance) of safety motives and reduced interest in the motives of "green" management. There is also differentiation in the structure of motives by category of personnel, which in general does not reduce the possibility of defining universal motivational components focused on achieving sustainable development goals.

Understanding the influence of force majeure factors (military actions, other disasters), further research will be directed at taking into account and determining the significance of the impact of the war factor (uncertainty and high risks to people's lives) on the structure of the motivational profile and the possibility of motivation to achieve sustainable development goals.

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Management of economic security of food industry enterprises as a direction of ensuring sustainable development

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Management of economic security of food industry enterprises as a direction of ensuring sustainable development

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Abstract. The article is devoted to the peculiarities of the economic security management of food industry enterprises as a direction of ensuring sustainable development of economic entities. It was determined that the food industry plays an important role in Ukraine's social and economic system; at the same time, food industry enterprises activity is characterized by the presence of negative trends. The essence and the components of the enterprise economic security were considered. The economic security is defined as a mechanism aimed at confronting threats and overcoming negative trends. The conceptual model of ensuring economic security of enterprises was proposed. In order to determine the key directions for increasing the level of economic security the model of dependence of economic security coefficient was formed using correlation and regression analysis. According to the model, the main factors of influence on food industry enterprises economic security formation are the growth rate of net profit, cash ratio and profitability of economic activity. The key measures for the formation of a constructive influence on the specified factors are proposed in order to increase the level of economic security of food industry enterprises.

1. Introduction

Conditions of functioning of Ukrainian enterprises are characterized by a high level of uncertainty and dynamism, aggravation of competition and crisis tendencies. The mentioned negative phenomena have significantly worsened due to the full-scale invasion of Russian Federation on the territory of Ukraine, which led to emergence of both physical and economic threats, increase in resources prices, in particular energy prices [1]. Thus, today Ukrainian enterprises are being under simultaneous influence of the following crisis factors: war, the consequences of a global pandemic, economic and social disruption, a change in the industrial paradigm, a new model of world perception, etc. [2]. The mentioned factors significantly complicate and threaten the economic entities functioning. Within this context the issues related to ensuring the stability and efficiency of Ukrainian enterprises functioning under martial law conditions and during post-war recovery acquire special relevance. An important place in the system of tasks and instruments of ensuring the stability of economic entities functioning and confronting crisis phenomena belongs to economic security management. Economic security is a comprehensive characteristic of enterprise operation condition which reflects the resilience of economic entity in relation to the action of threats of various genesis. Efficient management of enterprise economic security is a prerequisite of its stability, competitiveness, and is a tool of ensuring sustainable development. The role of economic security is also determined by the fact that it is a key characteristic from the point of view of sustainable functioning and achievement of the necessary development indicators both at the level of individual business entities and at the level of the state [3]. Thus, solving the issue of ensuring the economic security of economic entities is also relevant from the standpoint of the state policy formation.

The food industry, in turn, plays an extremely important role both in the economy of Ukraine and in ensuring the population's food security [4]. In particular, 19.56 % of the total volume of industrial production in Ukraine in January-September 2023 is accounted for the food industry; food industry entities provided 3.62 % of jobs in 2022 [5]. At the same time, the crisis trends that Ukraine is suffering from as a whole have also affected the functioning of food industry enterprises. The presence of negative trends is evidenced by the fact that in 2022, 32.3 % of food industry enterprises suffered a loss, and in the formation of property only 30.0 % of the assets of enterprises were formed at the expense of their own funds (equity) [5]. These indicators reflect the need to develop and implement measures aimed at increasing the stability and economic security of food industry enterprises.

Considering the role of the food industry in the economy of Ukraine and in the sphere of forming food security of the population, ensuring stable and sustainable development of enterprises of the defined industry through the economic security management will contribute to the achievement of the goals of sustainable development, namely SDG 2 "Zero Hunger", SDG 3 "Good Health and Well-being", SDG 8 "Decent Work and Economic Growth" [6]. Thus, the chosen topic of research is relevant and does not raise any doubts in view of the presence of significant crisis trends and the role of the food industry in Ukraine's economy.

2. Literature review

The issues of economic security management acquired special relevance for the post-Soviet countries, that determines the corresponding interest in scientific society. A significant number of publications devoted to issues of economic security have been published by Ukrainian scientists. Thus, Kryshtanovych et al. [7] consider ensuring economic security through the prism of marketing activities in public administration. The authors emphasize the necessity of implementation of marketing approach in the public administration processes due to the advantages provided by such implementation. The study also provides a model of the hierarchy of factors of influence on the implementation of marketing in public administration in the system of ensuring economic security [7]. The mechanism of economic security management is considered in the research of Zachosova, Kutsenko and Koval [2]. Based on the identified shortcomings of traditional approaches to economic security management, the authors propose the key components of the appropriate mechanism, taking into account the existing trends and operating conditions of business entities. The main components of the economic security management mechanism include the following: digitalization, automation, information processing, project management, personnel management, communications, research and innovations, and stakeholders [2].

An important component of the economic security management mechanism is assessment system of its level. Vasyltsiv et al. [8] define the peculiarities of assessment, analysis and ensuring agricultural enterprises' economic and financial security. The authors substantiate the methodical approach to assessment of the level of economic security taking into account the comprehensive nature of the studied characteristic, and propose measures to stabilize economic and financial security of agricultural enterprises based on the calculations [8]. The peculiarities of assessment of economic security level are considered in the research of Onyshchenko et al. [9], the main focus of which is the study of financial and credit institutions. Economic security is proposed to be assessed with the use of a skoring approach. The advantage of the study is the combination of both quantitative and qualitative indicators for assessing the level of economic security of economic entities [9]. Zhytar et al. [10] offers an approach to diagnosing the level of economic security, considering its following components: resource, social, market, and innovation. The specified components are presented through a set of individual indicators, which enables a detailed analysis of the criteria and factors of economic security. Scientists determine group and integral indicators of economic security, which can serve as a basis for the development of managerial decisions in the specified sphere [10].

The issue of the relationship between economic security and information technologies, which is explained by the active processes of digitalization of economic relations, attracted considerable attention of researchers. In particular, Samoilenko et al. [3] focused attention in their research on digital transformation as a driver of changes in approaches to enterprise economic security management. According to researchers, the economic security of an enterprise includes three main components: economic independence, stability, and development. Special attention in the article was paid to issues of ensuring and assessing the level of digital security of the enterprise [3]. Implementing digital technologies in business activities is a powerful tool for ensuring economic security. A special role in this context is played by the spread of IT in product sales, that is, the development of e-commerce. Alazzam et al. [11] propose the formation of the model of e-commerce development, as a perspective direction of economic security ensuring. According to the authors, the implementation of the e-commerce concept in the business activity provides additional options for stabilizing and expanding the economic entity functioning. Thus, to provide a system approach to the e-commerce development Alazzam et al. form a conceptual model of the respective process which includes three functional blocks, such as reorganization of e-commerce, ensuring cybersecurity, and integration of e-commerce into logistics [11]. The important role of information technologies is also emphasized by Zwaid et al. [12]. The research is focused on implementing accounting information systems and information technology to support the economic entity sustainability. In the example of Iraq's economic units, the authors define key challenges to the functioning sustainability: lack of sufficient financing, high level of bureaucracy, which leads to the growth of unofficial illegal activities, inefficient management and marketing activities due to the lack of appropriate knowledge, lack of sufficient data [12]. Thus, rational implementation of IT can potentially benefit in addressing these issues.

One of the important and perspective directions of economic security formation is transition to circular economy foundations. Thus, according to Kuzior et al. [13] implementation of innovations related to energy and resource saving, waste-free production can significantly reduce threats to the functioning of industrial enterprises. The authors determine that implementing the circular economy positively impacts various components of economic security of enterprise: management system and organizational structure, HR-management system, financial and investment systems, production support system, marketing and logistic systems [13].

Issues related to ensuring the economic security of enterprises are thoroughly considered by scientists of both Ukraine and other countries. In particular, these are issues related to ensuring stable, sustainable functioning and managing the financial stability and efficiency of both individual enterprises and countries as a whole.

The importance of issues related to the formation of economic security at the national level determines the presence of a significant number of publications devoted to the formation of economic security / sustainable development of the country and/or region. In particular, Lepers and Serrano [14] study financial instability at the macroeconomic level, adapting the research methodology to emerging economies. Authors provide extensive research of vulnerabilities in emerging economies [14]. Serban and Jianu [15] consider the economic security of the country using five key dimensions: demographic, climate, globalization and ITC adaptation, social, and economic. Authors propose an economic and social security index which provides the opportunity not only to define the positions and perspectives of Euro-Atlantic area countries but also to determine the key factors of influence [15].

Economic security and stability are often analyzed in the dialectical relationship with the energy component. Banna et al. [1] examine the relationship between energy security and economic stability, considering the effects of inflation and war (Russian invasion of Ukraine in particular). The research is based on studying the dataset of 68 countries. The authors define economic stability with the indicator of GDP growth rate, thus performing a macroeconomic approach to the stability issues [1].

The financial component of enterprise economic security is revised in the research of Zwolak [16]. The author analyses the peculiarities of SME functioning in Poland considering the issue of the EU fund support. Financial stability is also reviewed by Pera [17]. The author states that sustainable development of the enterprise is based on its financial stability, which determines the relevance of the research. The formula of the sustainable growth model is provided in the research, based on the financial indicators of the enterprise [17].

The importance of the food industry enterprises efficient functioning determined considerable scientific interest to the issues related to ensuring stable functioning of the respective business subjects. Montenegro and Young [18] provided a literature review on the issues of operational challenges in the food industry during the COVID-19 pandemic using ScienceDirect website. The main challenges were defined by the authors based on the conducted research. The proposed methods for the defined challenges are also generalized in the article [18]. Arenovych [19] considers the basics of socio-economic activity of food industry enterprises activity management. The author necessitates the urge for rational formation and use of resources. The quantitative estimation of the influence of various factors on the efficiency of food industry enterprises functioning is provided [19]. The drivers of economic performance of food industry enterprises are reviewed in the research of Trnková and Žáková Kroupová [20]. On the basis of analysis of 468 companies representing different branches of food industry the scientists provided a detailed analysis of the enterprises performance indicators [20]. Boonklum [21] provided research on key success factors of the food processing industry. The author defined three groups of factors which are crucial to food processing enterprise competitiveness as follows: resources (human, physical, financial), capabilities (marketing, managerial and relationship, innovation), competitive advantage [21].

Sustainable operating of food industry enterprises is considered in research of Sandberg, Alnoor and Tiberius [22], and Venturelly et al. [23]. In particular, Sandberg, Alnoor and Tiberius consider the interrelationship between environmental, social, governance ratings (ESG), and financial performance in European food industry. The authors used least squares regression method for analysis and estimated that higher ESG ratings are related to better financial performance. That conclusion determines the necessity to take into account the necessity of social responsibility concept implementation in the activity of enterprises [22]. Venturell et al. conduct their research through the prism of open innovation. According to the authors, open innovations contribute to the implementation of sustainable practices in the activity of food industry enterprises [23].

While recognizing the significant scientific contribution of these and other scientists, we should note that certain issues related to the management of the economic security of food industry enterprises remain insufficiently covered, and therefore require additional research to ensure the sustainable development of economic entities.

3. Objective of the research

The main objective of the research is to determine the priority directions for increasing the level of economic security of food industry enterprises using internal factors and development drivers. The defined objective involves solving the following tasks: to identify the essence and key components of economic security; to consider the model of ensuring economic security; to analyze the indicators of economic security of food industry enterprises; to define key factors of influence on the formation of the economic security level; to propose the directions of increasing the level of economic security of food industry enterprises.

4. Methodology

The methodological foundation of the research is the system approach, which involves consideration of economic security management as a component of the general management system. In addition, the following methods were used during the research: monographic – to study scientific publications related to the economic security of economic entities; analysis and synthesis – to study the trends in the formation of indicators of economic security of food industry enterprises; correlation and regression analysis – to study the influence of factors on the level of economic security of food industry enterprises; generalization – to form research conclusions; deduction – to substantiate directions for increasing the economic security level of food industry enterprises; graphical and tabular – to visualize the research results.

5. Results of the research

Economic entities of the food industry create a substantial share of Ukraine's GDP, ensure population employment, and form the country's food security. Ukraine has rich potential for the development of the food industry because of available resources, lands, and the development of agriculture, which is a main supplier for food industry enterprises. Taking into account the aforementioned, ensuring sustainable development of food industry enterprises is an important direction of social and economic development of Ukraine. Considering the fact that sustainable development unites three key components, namely economic, ecological, and social, within the framework of this study, we find it appropriate to focus attention on the economic component, namely on the economic security of food industry enterprises.

The main indicators of food industry enterprises' activity are presented in table 1.

Table 1. Indicators of activity of food industry enterprises of Ukraine (according to the data of State Statistical Service of Ukraine [5]).

Indicator	Years					Deviation 2022 to 2018	
	2018	2019	2020	2021	2022	+/-	%
Volumes of sold products, UAH million	547365.7	571914.3	627520.2	769949.9	697233.4	149867.7	27.4
Number of active economic entities, units	14681	15309	15190	15109	13023	-1658.0	-11.3
Number of employees, persons	331261	331339	328475	321814	275009	-56252	-17.0
Net profit (loss), UAH million	9624.4	14705.8	-841.9	14149.6	3101.3	-6523.1	-67.8

According to the data presented in table 1, substantial negative trends are present in the activity of food industry enterprises. In particular, the decline of economic entities number by 11.3 % is observed in 2022 compared to 2018, which led to a decrease of employees by 56252 persons (17 %). The economic entities of the industry have formed net profit during the analyzed period (except for the 2020), however, there is a decline of net profit by UAH 6523.1 million or by 67.8 % in 2022 compared to 2018. The only indicator reflecting a positive increasing trend is sold product volumes (by UAH 149867.7 million or by 27.4 %). At the same time, we should note that one of the factors influencing the increase in volumes of sold products is the inflationary growth of prices for products of food industry enterprises (the inflation index in 2022 was estimated as 26.6 % [24]), so the specified increase is controversial.

Thus, the study of the main indicators of food industry enterprise activity in 2018-2022 provided an opportunity to reveal the presence of significant negative trends, primarily related to the full-scale invasion of the Russian Federation on the territory of Ukraine. According to Arenovych, the key factors of negative impact are the following [19]:

- decrease of raw materials accessibility;
- increase of the costs related to security providing;
- loss of markets;
- logistic processes efficiency decrease;
- personnel loss;
- changes in legal environment;
- consumers demand decrease.

The approach of Montenegro and Young to the definition of key challenges for food industry enterprises can also be applied to the realities of Ukrainian business subjects. The scientists specify the following challenges [18]:

- food safety – this challenge is totally applicable to Ukrainian enterprises as the war risks form a significant impact on both crop and livestock production (e.g., soil contamination, inability to comply with all safety requirements during production, etc.);
- production – is due to decreased resources accessibility, insufficient financial resources, physical threats;
- pricing – such a challenge is due to the decreased level of solvent demand of Ukraine population as well as to the population migration, including refugees to different countries;
- logistics – a lot of logistic chains were disrupted due to the war. Another issue regarding logistic is the essential increase in fuel prices which leads to enterprises costs increase;
- food systems survivability – defines all the risks and threats to the food industry enterprises functioning.

The presence of negative trends indicates the need to develop effective mechanisms for countering crisis phenomena and ensuring the stability and sustainability of the development of economic entities. We believe that one of the key such mechanisms is the management of the economic security of enterprises.

Economic security is a comprehensive characteristic of the enterprise activity, which defines its ability to ensure stable functioning and to confront threats. Economic security is a prerequisite for the development of economic entities, as it ensures the functioning stability and protection of economic interests, resources and rights, as well as the opportunity to confront external and internal threats [9].

The concept of economic security is very dynamic, as it is inextricably linked to the challenges of today [15]. In general, scientists define economic security as a state (a state in which balance and stability are preserved; a state of enterprise development; a state of the most efficient use of resources) or protection (of the business entity from threats, from the negative impact of the external environment).

To counteract the entire set of modern threats and ensure the necessary level of economic security, it is expedient to build a comprehensive system of economic security, for which it is necessary to fully utilize the resources of all structural divisions of the enterprise, as well as the capabilities of external stakeholders, including state authorities and management, subjects of the non-state security system [25]. Sustainable development, especially under modern functioning conditions, is related to the uncertainty of the situation, that is to the risk. Ensuring sustainable development is based on considering and predicting possible changes in the internal and external environment of the enterprise.

Economic security is formed as a condition which is achieved through the following functional goals:

- economic development (extended reproduction of the main business processes, namely innovative modernization of production, implementation of investment activities, development of intellectual potential, increase of competitive advantages in conditions of aggravated competition and uncertainty of the business environment, which ensures the achievement of quantitative and qualitative targets of the enterprise, etc.);
- financial and economic balance (balanced functioning at different stages of enterprise life cycle and in the cyclical conditions of economy, in particular ensuring sufficient financial stability and economic autonomy, maintaining an optimal capital structure, ensuring one's own financial interests and defined goals);
- managerial goal (ensuring the productivity of management, and formation of an effective organizational structure of enterprise management);
- personnel goal (implementing a proactive personnel management policy);
- ecological goal (compliance with the policy of sustainability in the process of minimizing the destructive impact of the results of production and economic activity on the state of the environment);
- harmonious and adaptive goal (flexible and harmonious interaction of the enterprise with the external environment for timely consideration of the influence of external environmental factors in order to maintain the internal balance of the functioning);
- information and security goal (building a legal, information and security environment based on high-quality legal protection, ensuring the protection of the information field, commercial secrets, and achieving a sufficient level of information support for the work of all units of the enterprise; effective organization of the security of the enterprise's personnel, its capital and property, and also commercial interests);
- economic freedom (synergy of economic self-sufficiency and responsibility: formation of high-quality resource potential of the enterprise and control over its rational use to achieve set goals in an unstable business environment).

On the basis of the aforementioned, we propose the following conceptual model of ensuring the economic security of the enterprise (figure 1).

The model of ensuring the economic security of the enterprise is presented by a holistic system through the set of interrelated elements (economic entities, subjects and objects of management, resources, technologies, business operations, innovative objects of activity), the entirety and interaction of which is oriented on achieving the sustainable development with the aim of preventing threats and dangers in the external and internal environments at the micro level (enterprise) and macro level (state).

Modern business functioning conditions characterized by the high level of complexity, volatility and exacerbation of crisis tendencies require adaptation of existing approaches to economic security management. According to Zachosova, Kutsenko and Koval the following characteristics should be inherent to the economic security management system: guarantees and flexibility; utility and rationality; activity and adaptability; resources and results; digitalization; information and innovation; automation and updating; non-linearity and independence [2]. Formation of the economic security management model taking into account the mentioned characteristics is a vital prerequisite for achieving the stability of functioning and sustainability of the development of economic entities.

Economic security significantly depends on the condition and dynamics of both external and internal environment [3]. Considering this, issues related to ensuring interaction with external environment acquire special relevance in the economic security management system. Ensuring interaction with the external environment should be provided through the appropriate mechanism, which includes economic, ecological, and adaptive instruments, which in their

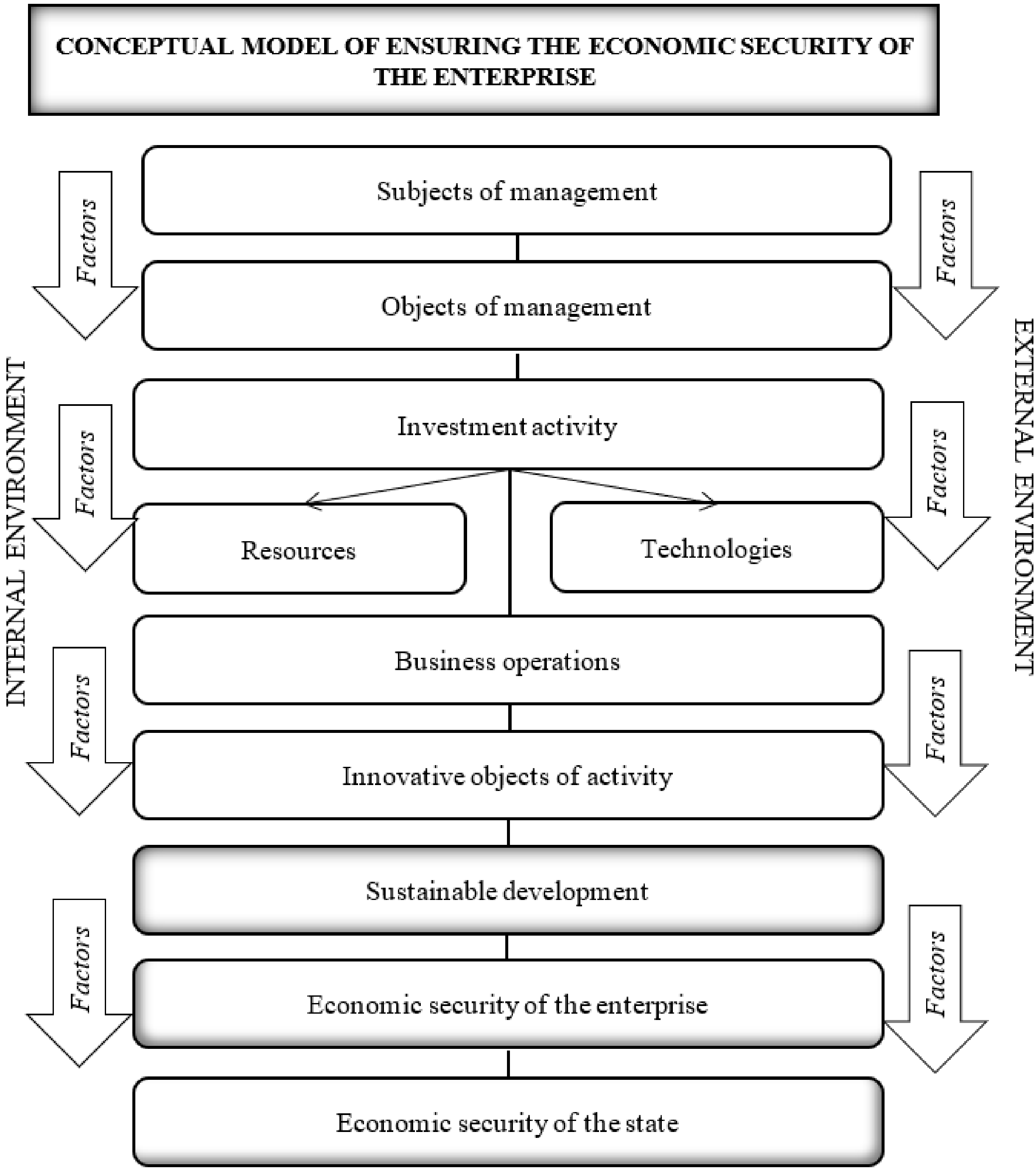

Figure 1. Conceptual model of ensuring the economic security of the enterprise.

entirety contribute to achieving sustainable development and a sufficient level of economic security [26]. Formation of the qualitative new system of interaction with stakeholders is also important in the context of ensuring economic security, that will provide effective communication and further interaction with stakeholders.

An important component for the management is the assessment of economic security level, considering the necessity of understanding the current condition, weaknesses, and potential threats in the enterprise activity. The complexity of the issues related to the assessment of enterprise economic security is due to the fact that the studied category is uncertain, dynamic, and comprehensive from the quantitative estimation standpoint [16]. As of today, there is a significant number of methods of assessment of economic security level. At the macroeconomic level, Lepers and Serrano define financial system stability using the vulnerability index [14]. Vasyltsiv et al. propose composite approach to the estimation of economic security level of agricultural enterprises considering the following elements: resources, investment, money and credit, debt, economy, insurance [8]. Kuzior et al. provide the approach to assessing the level of economic security using 3R model – Resource supply, Recycling, Results (effectiveness), which provides an opportunity for enterprise to define directions of economic security formation [13]. Onyshchenko et al. define economic security through the combination of quantitative (financial component) and qualitative (informational, marketing, personnel components) characteristics. For the assessment the scientists offer use of scoring approach which envisages calculating of points on the basis of assessment of economic entity activity indicators using Harrington scale [9]. An integral approach to the assessment of economic security level is proposed by M. Zhytar et al. The authors consider the following dimensions for determining the integral indicator of economic security of enterprises: resource, social, market, innovative [10].

Thus, we can conclude that today, there is a significant number of different approaches to the assessment of economic security level of economic entities, which is determined by the complexity and multifacetedness of this characteristic. With the aim of defining key factors of impact on the level of economic security and forming the respective propositions, we believe it is expedient to use an express approach to the estimation of conditions and criteria of economic security, which will be based on the limited range of the indicators of financial nature.

For a more detailed study of factors of the formation of food industry enterprises' economic security, we will analyze key indicators of economic security and stability of specific economic entities. Twelve enterprises were chosen for the research, representing different branches of food industry, namely: confectionery industry (PJSC "Vinnytsia Confectionery Factory", JSC "Zhytomyr Lasoshchi", PJSC "Kharkiv Biscuit Factory"), dairy industry (JSC "Zhytomyr Butter Plant", ALC "Yagotynsky Butter Plant", LLC "Loostdorf"), meat processing industry (LLC "Saltivsky Meat Processing Plant", LLC "Hlobyne Meat Processing Plant", ALC "Meat Processing Plant "Yatran"), bakery industry (PJSC "Concern Khlibprom", LLC "Kyivkhlib", LLC "Mykolaiv Bakery № 1"). The choice of the enterprises is determined by the following:

- the enterprises proposed for the study represent the most important branches of the food industry;
- financial reports of the specified enterprises are in public access, which makes it possible to obtain and use data necessary for calculations;
- the enterprises represent different regions of Ukraine, which provides an opportunity to realize a comprehensive approach within the research.

We propose to identify the key factors of the formation of economic security using correlation and regression analysis, which provides an opportunity to determine the relationship between dependent variable and independent variables. The economic security coefficient was chosen as a dependent variable (Y) which in its essence represents the difference between actual and breakeven volumes of enterprise activity. We believe that the choice of this indicator as a dependent variable is substantiated from the standpoint of the necessity to provide enterprise activity profitability, as well as to form a reserve of financial sufficiency for countering crisis phenomena.

We will base the determination of the factors of influence (independent variables) on the level of economic security on financial indicators since the financial component of economic security is one of the most important from the point of view of ensuring sustainable development. Business entities seeking to implement the principles of sustainable development in their activities must be financially stable because financial stability is the basis for ensuring continuous functioning [17].

As the independent variables the following indicators were chosen:

X_1 – net revenue growth rate, coef.;
X_2 – net profit growth rate, coef.;
X_3 – equity growth rate, coef.;
X_4 – autonomy coefficient, coef.;
X_5 – coefficient of financial self-sufficiency, coef.;
X_6 – current ratio, coef.;
X_7 – cash ratio, coef.;
X_8 – return on sales, coef.;
X_9 – economic activity profitability, %;
X_{10} – ratio between receivables and payables, coef.

The choice of the independent variables was determined by the following:

- the chosen indicators reflect the most important characteristics of the financial state of the enterprise, which, in its turn, significantly defines the economic security level;
- the growth rate indicators characterize the enterprise ability to ensure stable development and sustainable functioning;
- utilization of ratios makes it possible to compare enterprises with different scale of activity;
- the defined indicators can be calculated on the basis of public financial statements data which provides accessibility of data for calculations and further analysis.

Calculations for the analysis will be carried out for 2020-2022, which will make it possible to determine the key trends in the functioning of food industry enterprises. The total number of observations is 36, which ensures the representativeness of the raw data for correlation and regression analysis.

The initial data for the analysis are presented in table 2.

In general, based on the results of the analysis of the calculated data, we can draw the following conclusions regarding the trends in the functioning of the food industry enterprises of Ukraine:

- in the activities of a significant number of enterprises (6 out of 12 studied), there is a decrease in the level of economic security in 2022 compared to 2020. Taking into account the fact that in 2020 crisis phenomena related to the COVID-19 pandemic were observed, such trends are extremely threatening from the point of view of ensuring the stability of functioning and sustainable development of economic entities;
- a large part of the enterprises is characterized by a low level of financial stability, which is manifested in a significant share of financing at the expense of liabilities;
- with a mostly sufficient level of general liquidity, a low level of absolute liquidity is observed, which indicates a lack of cash in the activities of food industry enterprises;
- in the activity of a significant number of enterprises from among those studied, there is a decrease in the level of profitability of economic activity in 2022 compared to 2020. Thus, in general, we are talking about a trend towards a significant decrease in the efficiency of food industry enterprises.

Table 2. Initial data for correlation and regression analysis of food industry enterprises (based on public reporting data [27]).

Years	Y	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
PJSC “Vinnytsia Confectionery Factory”											
2020	0.05	1.17	0.60	1.00	0.89	-0.29	0.58	0.00	0.07	0.28	1.36
2021	0.02	1.18	0.41	1.00	0.84	-0.34	0.66	0.00	0.07	0.10	0.91
2022	-0.35	1.04	-13.03	0.99	0.87	0.20	1.10	0.00	0.08	-1.09	2.33
JSC “Zhytomyr Lasoshchi”											
2020	0.22	0.88	2.06	0.85	0.50	0.05	1.05	0.00	-0.01	3.52	1.22
2021	0.01	0.97	0.06	0.91	0.35	0.02	1.03	0.01	0.15	0.24	1.10
2022	0.08	1.63	7.17	0.95	0.21	-0.01	0.99	0.00	0.14	0.01	1.13
PJSC “Kharkiv Biscuit Factory”											
2020	0.42	0.93	1.95	1.09	0.96	0.94	18.92	4.04	0.15	6.83	10.76
2021	0.33	1.17	0.76	1.06	0.95	0.93	15.14	2.76	0.12	4.36	10.47
2022	0.45	0.84	1.30	1.08	0.95	0.93	16.68	4.95	0.14	6.92	9.06
JSC “Zhytomyr Butter Plant”											
2020	0.27	1.00	0.97	1.12	0.73	0.26	1.45	0.11	0.25	6.37	3.64
2021	0.12	1.11	0.45	1.05	0.66	0.26	1.38	0.09	0.22	2.50	3.27
2022	0.34	0.93	3.43	1.16	0.69	0.44	1.78	0.83	0.31	9.75	4.17
ALC “Yagotynsky Butter Plant”											
2020	0.32	1.00	0.70	1.12	0.38	0.07	1.36	0.01	0.16	4.26	1.65
2021	-0.27	0.98	-1.49	0.89	0.34	0.08	1.43	0.04	0.10	-1.95	2.38
2022	0.32	1.20	3.46	1.29	0.34	0.16	1.47	0.01	0.17	4.31	2.06
LLC “Loostdorf”											
2020	0.17	1.04	0.76	1.20	0.66	0.29	2.25	0.52	0.31	5.06	2.09
2021	0.07	1.19	0.36	1.06	0.57	0.14	2.17	0.18	0.28	1.48	2.16
2022	0.19	0.97	2.92	1.32	0.68	0.33	2.49	0.61	0.25	4.55	2.19
LLC “Saltivsky Meat Processing Plant”											
2020	0.14	1.15	1.14	1.17	0.39	0.00	1.00	0.12	0.17	2.38	1.49
2021	0.06	1.33	0.56	1.08	0.36	-0.29	0.98	0.06	0.16	1.02	1.51
2022	0.09	1.13	0.97	1.62	0.34	-0.09	1.03	0.01	0.09	0.90	1.24
LLC “Hlobyne Meat Processing Plant”											
2020	0.21	1.04	4.69	1.70	0.23	-0.69	0.65	0.04	0.25	5.92	0.48
2021	0.31	1.20	0.62	1.27	0.29	-0.44	0.76	0.05	0.25	3.34	0.74
2022	0.18	1.42	1.94	1.25	0.34	-0.39	0.84	0.06	0.24	4.10	0.67
ALC “Meat Processing Plant “Yatran”											
2020	0.10	0.98	1.03	1.10	0.77	0.58	2.39	0.15	0.25	2.31	1.56
2021	-0.22	1.12	-2.43	1.14	0.75	0.53	2.11	0.17	0.23	-3.63	1.34
2022	0.14	1.02	1.82	1.30	0.82	0.63	2.71	0.41	0.22	3.08	1.45
PJSC “Concern Khlibprom”											
2020	0.09	0.94	0.43	1.20	0.36	-0.97	1.03	0.04	0.37	3.30	0.63
2021	0.03	1.16	0.39	1.06	0.35	-1.01	0.97	0.03	0.31	1.16	0.56
2022	0.06	1.15	1.24	1.07	0.35	-0.76	1.03	0.11	0.34	1.24	0.46
LLC “Kyivkhlib”											
2020	0.08	0.98	0.56	1.38	0.20	0.05	1.06	0.04	0.36	2.73	2.57
2021	-0.08	1.18	-1.92	0.75	0.07	-0.02	1.07	0.05	0.29	-2.01	2.71
2022	0.05	1.24	1.82	1.28	0.07	-0.15	0.93	0.01	0.30	1.35	1.93
LLC “Mykolaiv Bakery № 1”											
2020	0.04	1.78	0.62	1.13	0.03	0.02	1.03	0.00	0.19	0.33	0.93
2021	0.02	1.33	0.53	1.07	0.02	0.01	1.02	0.00	0.10	0.13	1.00
2022	0.46	0.61	1.97	0.87	0.02	0.01	1.01	0.12	0.20	5.13	0.97

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}
Y	1.00										
X_1	-0.30	1.00									
X_2	0.62	0.12	1.00								
X_3	0.20	0.05	0.28	1.00							
X_4	0.11	-0.33	-0.22	-0.07	1.00						
X_5	0.25	-0.24	-0.06	-0.14	0.56	1.00					
X_6	0.46	-0.23	0.06	-0.07	0.54	0.64	1.00				
X_7	0.50	-0.27	0.09	-0.05	0.53	0.61	0.97	1.00			
X_8	0.07	-0.05	0.16	0.30	-0.23	-0.27	-0.18	-0.14	1.00		
X_9	0.87	-0.43	0.46	0.33	0.25	0.26	0.40	0.47	0.22	1.00	
X_{10}	0.43	-0.25	0.00	-0.12	0.56	0.71	0.94	0.91	-0.15	0.44	1.00

To identify the key factors when building the model, the next step will be an analysis of the presence of relationships between factor characteristics, that is, a multicollinearity test. For calculations, we will use the built-in MS Excel data analysis package. The results of the analysis are given in table 3.

According to the calculations, we should note that the relationships of varying degrees of influence are determined between the dependent variable and independent variables. The most significant is the relationship between the coefficient of economic security (Y) and the profitability of economic activity (X_9), which is quite logical given the peculiarities of calculating the coefficient of economic security. A significant relationship is also observed between the dependent variable and the net profit growth rate (the linear correlation coefficient is 0.62). The relationship with variables X_6 (current ratio) and X_7 (cash ratio) is also significant. At the same time, we should note that factors X_6 and X_7 are multicollinear, i.e. interdependent, therefore, it is not appropriate to include both factors in the model. As the linear correlation coefficient of X_6 factor is 0.46 and the respective coefficient of X_7 factor is 0.5 we can conclude that the relationship of X_7 factor with the dependent variable is more significant. Thus, we should exclude X_6 factor from the consideration. So, for the further construction of the model, we use three factors: X_9 – profitability of economic activity, X_2 – net profit growth rate, X_7 – cash ratio. Based on the results of the regression analysis, the following equation was formed:

$$Y = -0.0065 + 0.0192X_2 + 0.0271X_7 + 0.0418X_9, \quad (1)$$

where Y – economic security coefficient, coef.; X_2 – net profit growth rate, coef.; X_7 – cash ratio, coef.; X_9 – economic activity profitability, %.

According to the regression equation parameters, the determination coefficient $R^2 = 0.84$; that is, 84 % of the variance of the values of the dependent variable (economic security coefficient) is explained by the obtained equation. We believe that the rest of the dependent variable volatility is explained by the impact of external environment factors. According to the results of the F-test (Fisher's test), the constructed model is considered adequate for the sample data because $F_{fact}(55.09) > F_{crit}(2.9)$ (with a probability of error of 0.05).

Thus, based on the conclusion about the adequacy of the built model, we can determine the priority directions for increasing the level of economic security of food industry enterprises:

- ensuring high growth rates of net profit;
- increase in the level of absolute liquidity;
- increase in the level of profitability of economic activity.

It is worth noting that measures aimed at ensuring high growth rates of net profit and increasing the level of profitability are compatible, because net profit is one of the factors in determining the level of profitability of economic activity. Therefore, it is advisable to reduce the key measures for increasing the level of economic security to two directions. Let's consider them in more detail.

1. *Increasing the efficiency of economic activity.* This direction will contribute both to ensuring high growth rates of net profit and to increasing the level of profitability of economic activity. When determining measures to increase the level of the enterprise profit, it is advisable to take into account the factors influencing the formation of the financial result. In particular, Pavlyuk proposes to divide the relevant factors into external, that is, those that have a source of genesis outside the enterprise and are uncontrollable from the point of view of the management of the business entity, and internal, which have a source of origin within the enterprise. In addition, the scientist proposes to divide internal factors into non-productive and productive (extensive and intensive) [28]. Another perspective for increasing the efficiency involves technical and scale efficiency, and technological change [20]. The strategy and individual measures to increase the profit level of food industry enterprises should be formed taking into account the relevant factors in order to achieve the target result.

   Within the framework of this direction, we consider it expedient to propose the following measures:

   1.1. *Search for new sales markets and diversification of activities.* These measures are aimed at increasing the income level of food industry enterprises. The war on the territory of Ukraine has significantly affected the logistics and sales conditions of enterprises, placing special emphasis on the need to review existing and form new economic ties. In particular, reorientation to other segments of the domestic market and/or search for foreign partners is possible. Taking into account the processes of globalization and digitalization, the search for foreign partners is significantly simplified. For example, in June 2017, Ukraine joined the European Enterprises Network [29], a business network that facilitates partnerships and consortia in business. With the help of the appropriate resource, Ukrainian business can search for requests and / or create proposals for foreign business partners.

   Diversification of activities through the introduction of new types of products is also an important component of this measure. Taking into account the above proposal regarding the search for foreign partners, it is expedient for food industry enterprises to consider expanding the assortment with those types of products that, firstly, will meet the requirements and standards not only of Ukraine, but also of other countries, and secondly, will be suitable for long-term storage and transportation.

   1.2. *Expanding the presence of enterprises on the Internet.* Today, the world as a whole and Ukraine in particular have already entered the era of digitalization, which puts forth appropriate demands for digitalization of economic and social relations. Ukraine has significant achievements in this area that contribute to business development, for example, the Diia.Business service, a large-scale national project for the development of entrepreneurship and exports, initiated by the Ministry of Digital Transformation in February 2020 [30]. At the same time, it is worth noting that at the level of individual business entities, the problem of representation in the digital space remains relevant. Positive developments in this area are evidenced by the fact that all 12 studied enterprises have their own websites, where consumers can familiarize themselves with the range of products and key information about business entities. At the same time, only 3 enterprises have online stores: PJSC "Vinnytsia Confectionery Factory"; JSC "Zhytomyr Lasoshchi"; ALC "Meat Processing Plant "Yatran" (delivery only in Kyiv is possible). It is clear that the products of food industry enterprises have their own specifics, which limits the possibilities for their sale through online stores (for example, storage periods, the need to keep the temperature regime during transportation, etc.), however, in our opinion, at least partial use of e-commerce could stimulate sales. Options of such partial use include the geographical localization of product sales (an example is the online store of ALC "Meat Processing Plant "Yatran") or the limited range of products that can be purchased through the online store.

1.3. *Optimization of economic activity costs.* This measure is the most complex and the most difficult at the same time, considering the variety of costs which are formed in the enterprise activity. Thus, the most expedient way of this measure implementation is the conducting an in-depth analysis in order to identify non-productive costs and to direct measures to the relevant specific costs of the enterprise. In the most general form, reducing the costs of economic activity can be achieved with the help of the following steps [31]:
    - control of the amount and processes of cost formation for each element of the value chain;
    - improvement of the value formation chain by elimination of non-productive and excessive costs;
    - economy of scale;
    - effect of experience.

    At the same time, we consider it expedient to emphasize the fact that specific measures to optimize costs depend significantly on what costs they are aimed at (for example, costs for energy supply, raw materials, labor costs, etc.).
1.4. *Implementation of corporate social responsibility (CSR) concept in the enterprises management system.* As Sandberg, Alnoor and Tiberius found in their research, the financial performance of food industry enterprises is under positive impact of ESG (environmental, social, governance) ratings. The companies with high level of CSR development tend to have a better financial performance [22]. Within this context we believe that it is expedient to implement sustainable practices in the activity of food industry enterprises. Such sustainable practices may include the following:
    - to implement open innovations in order to promote sustainability in functioning of the food industry enterprises [23];
    - to increase the food safety management through the implementation of appropriate systems and techniques (e.g., HACCP system);
    - to ensure compliance with the rights of employees and other stakeholders;
    - to implement an effective waste management system which will provide for decrease of pollution and minimize negative impact on environment;
    - to improve resource management in order to optimize the amount of used in the activity resources;
    - to support personnel and local communities with various programs.
1.5. *Increasing the level of enterprise competitiveness.* The enterprise competitiveness reflects its capacities to participate in competition relations, thus, to operate efficiently in the market. So, there is mutual relationship between the efficiency of economic activity and the level of competitiveness. According to N. Boonklum, the key success factors for boosting the competitiveness level are the following: resources (human, physical, financial), capabilities (marketing, managerial and relationship, innovation), competitive advantage [21].

2. *Increasing the level of absolute liquidity.* The cash ratio is important from the point of view of ensuring stability and solvency of any enterprise. In particular, it indicates what share of current liabilities the company is able to repay with the help of available highly

liquid assets. According to the table 2 we should note the negative situation in the field of formation of liquidity indicators of food industry enterprises. In particular, only PJSC "Kharkiv Biscuit Factory" and LLC "Loostdorf" are distinguished by a high level of absolute liquidity during 2020-2022. Two more enterprises (JSC "Zhytomyr Butter Plant" and ALC "Meat Processing Plant "Yatran") achieved a sufficient level of absolute liquidity in 2022. At the same time, the other 8 enterprises throughout the entire period under study are characterized by a low or even zero level of absolute liquidity, which determines the relevance of this direction of increasing the level of economic security. We believe that in order to increase the level of absolute liquidity, it is advisable to implement the following measures:

- optimization of stocks with the aim of freeing up cash to increase the level of absolute liquidity;
- implementation of advanced inventory management systems (for example, ERP systems, just-in-time, lean production, etc.);
- optimization of receivables with the allocation of overdue and bad debts and the application of the factoring procedure to transfer part of the debt into cash;
- improvement of payment discipline in order to avoid the accumulation of a significant amount of receivables;
- optimization of current debt through the maximum possible use of long-term borrowed capital instead of short-term;
- reduction of the duration of the operating cycle. This measure is related to the aforementioned as the duration of the operating cycle depends on the period of turnover of stocks as well as on the period of receivables turnover. Thus, the following steps can be taken in this sphere: implementation of economically substantiated stock norms; compliance with the principle of optimal price-quality ratio when forming stocks; improvement of logistics management and sales policy of enterprises; intensive reproduction of the elements of the enterprise potential; active introduction of aspects of the circular economy; effective management of receivables; 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 [32].

If to apply the mentioned measures from the proposed approach standpoint to the activity of specific enterprises, we can conclude the following. The priority measures for enterprises with the decline in the level of economic security in our opinion should be the following:

- PJSC "Vinnytsia Confectionery factory" – increasing the efficiency of economic activity, which may include the following measures: optimization of economic activity costs, increasing the level of corporate social responsibility;
- JSC "Zhytomyr Lasoshchi" – increasing the efficiency of economic activity: search for new sales markets, optimization of economic activity costs, increasing the level of corporate social responsibility;
- LLC "Saltivsky Meat Processing Plant" – increasing the efficiency of economic activity and of liquidity: search for new sales markets, expanding the presence on the Internet, optimization of economic activity costs, increasing the level of corporate social responsibility; optimization of stocks, reduction of duration of the operating cycle;
- LLC "Hlobyne Meat Processing Plant" – increasing the efficiency of economic activity: search for new sales markets, expanding the presence on the Internet, optimization of economic activity costs, increasing the level of corporate social responsibility;
- ALC "Meat Processing Plant "Yatran" – increasing the efficiency of economic activity: search for new sales markets, optimization of economic activity costs, increasing the level of corporate social responsibility;

- PJSC "Concern Khlibprom" – increasing the efficiency of economic activity: search for new sales markets, optimization of economic activity costs, increasing the level of corporate social responsibility;
- LLC "Kyivkhlib" – increasing the efficiency of economic activity and of liquidity: search for new sales markets, expanding the presence on the Internet, optimization of economic activity costs, increasing the level of corporate social responsibility; optimization of stocks, reduction of duration of the operating cycle.

As for the enterprises with the increase in economic security level priority steps can vary, but the main stress should also be put on the increasing of efficiency, and liquidity.

The given list of measures is not exhaustive and can and should be specified taking into account the peculiarities of the activity and the structure of the balance sheet of a particular business entity.

6. Conclusions

As a result of the conducted research, we can conclude the following.

1. The food industry plays an extremely important role in the economy of Ukraine, which is explained both by its contribution to the total volume of manufactured industrial products and by its importance from the point of view of food security formation. At the same time, food industry enterprises are characterized by negative trends, which are manifested in the reduction of the number of economic entities, as a result – a decrease in the number of employees and a significant decrease in net profit. The above determines the expediency of finding effective solutions to increase the level of economic security of food industry enterprises as a way to ensure the sustainable development of economic entities.
2. Economic security is a complex characteristic of an enterprise's activity, which determines its capabilities to ensure the stability of functioning and to counter threats. The functional areas of manifestation of economic security include economic development, financial and economic balance, management, personnel, environmental, adaptive, information and security components, and economic freedom.
3. A conceptual model for ensuring the economic security of the enterprise was proposed, which is based on the active implementation of investment activities, covers economic operations, and innovative objects and promotes the sustainable development of the enterprise. The key characteristics that should be inherent in managing the enterprise's economic security were determined.
4. In order to identify factors influencing the formation of food industry enterprises economic security, an analysis of key financial indicators affecting the formation of stability and development prospects of economic entities was carried out. The corresponding analysis was carried out on the basis of data from the financial statements of 12 enterprises representing various branches of the food industry for 2020-2022. As a result of the study, it was found that 6 enterprises out of 12 studied are characterized by a decrease in the level of economic security and profitability, and a significant number of business entities have low levels of financial stability and absolute liquidity.
5. In order to define the influence of the considered indicators on the formation of the level of economic security of food industry enterprises, the factors characterized by the highest influence on the dependent variable (coefficient of economic security), namely the net profit growth rate, the cash ratio, the profitability of economic activity, were identified using correlation analysis. With the help of regression analysis, a linear model of the dependence of the coefficient of economic security on the specified factors was built, which made it possible to propose key measures to increase the level of economic security of food industry enterprises.

6. The practical implementation of the developed approach implies definition of the particular set of measures for food industry enterprises in order to ensure the increase of the economic security level, defined on the basis of the analysis results. It was determined that the main measures to increase the level of economic security should be aimed at increasing the efficiency of economic activity (the search for new sales markets and diversification of activities; expanding the presence of enterprises on the Internet; optimizing the costs of economic activity; implementation of the CSR concept in the management system; increasing the level of enterprise competitiveness) and increasing the level of absolute liquidity (improvement of stocks and receivables management; optimization of current payables). If to specify the measures for the analyzed enterprises, we can propose the following: the priority steps for PJSC "Vinnytsia Confectionery factory", JSC "Zhytomyr Lasoshchi", LLC "Hlobyne Meat Processing Plant", ALC "Meat Processing Plant "Yatran", PJSC "Concern Khlibprom" should be oriented at increasing the efficiency of economic activity. LLC "Saltivsky Meat Processing Plant" and LLC "Kyivkhlib" should also pay massive attention to the measures aimed at increase of liquidity level.
7. Prospects for further research are in the field of substantiating strategies for managing the economic security of food industry enterprises using a matrix approach and forming a specific set of tools for managing the economic security of food industry enterprises.

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The income, consumer spending and wellbeing of Ukrainian households

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The income, consumer spending and wellbeing of Ukrainian households

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Abstract. This article is devoted to the refinement of factors determining the structure of Ukrainian households' consumption spending and approaches to interpretation of shifts in such structure in context of population well-being. It contains analysis with using indexes of real volume of consumption, combined with the localization of causes determining fluctuations in relative prices by commodity group. The results of such analysis should create preconditions to clarify the contribution of certain industries and commodity groups in the dynamics of consumer welfare. For estimating the income and price elasticity of consumption by wide aggregated commodity groups the linear modeling was used. Authors have used quite simple linear additive function, the first element of which is close to Working function, and the second – a very simplified replacement of Theil proposed mathematical tools for incorporating relative prices into mentioned model. The elasticity coefficients, calculated on basic our model were compared with coefficients obtained by Seale Jr. and Regmi [1]. For five commodity categories, we also compared the actual indices of real changes in quantity of consumption with similar indicators, which were calculated on basis the elasticity coefficients, obtained in our and mentioned works. Elasticity coefficients are designed by Seale Jr. and Regmi [1] for "Food" and "Furnishings, household equipment and routine maintenance of the house" have demonstrated quite good explanatory power. But estimated figures for both models clearly deviate from the actual values, which were observed for "Clothing and footwear", as well as for "Housing, water, electricity, gas and other fuels". At last, we try to explain the causes determining such deviation of actual scale of consumption comparing with calculated on basis elasticity coefficients and create precondition for better understanding connection of observed change in consumption of such commodity group with level of population's well-being.

1. Introduction

The improvement of analytical tools for the estimation of the population's well-being is a significant precondition for the development of any state policy: it provides feedback and information about how the certain policy implementation affects the living conditions characteristics of the policy's target group. At the same time, the approaches to the quantitative assessment of the well-being aggregate function, or individual components of well-being, remain a promising field of scientific research. In the focus of our article is the connection between shifts in consumption behavior, in the structure of households' spending, and price/income elasticity of certain commodities demand – as factors and economical well-being of the population – as a dependent variable. The aim of this article is to clarify to what extent analytical tools that demonstrate a good explanatory power regarding changes in consumer behavior and well-being in conditions of long-term growth of real incomes of the population remain relevant in conditions of stagnation or even a reduction in the purchasing power of households.

2. Literature analysis

The vast majority of current research in consumer spending of households has considered them as a dependent parameter, reflecting the impact of factors, among which there are almost always two mandatory: income (sometimes – the total expenditure) of households and relative prices by commodity groups. Specificities of the individual studies are largely linked to choice of additional factors, included in the model and structure of mathematical tools, used for the simulation. The similar generalizations is contained in the [2]: "The predominant method used in applied studies of demand has been the demand systems approach, in which a system of equations is used and the dependent variable is household spending on a particular good (usually expressed as a budget share), while the independence variables are the relative prices of other goods, household income (discussed below) and the household's demographic characteristics. The core theory underpinning this approach is based on a view that these expenditures are an outcome of a single, representative household that maximizes its utility in each period by spending on the observed categories according to a linear budget constraint".

Such researches are based mainly on the works of Theil, Slutsky, Working, Hicks, which have been transformed into such prevalent tools as multistage budgeting, model Florida-Preference Independence (PI) and Florida-Slutsky model. Illustrative examples of such tools' application for the study of national consumption patterns and their comparative analysis are given by works [1, 3, 4].

The results of these studies have confirmed that levels of income and relative prices have high explanatory power regarding the differentiation of consumer spending patterns of households around the world. The results obtained have high value in the context of explaining consumer response to fluctuations in relative prices and income (through evaluation the relative prices and income elasticity of demand for different product groups) as well as in the context of predicting potential of growth for each industries, which are determined by patterns of consumer spending (as a significant component of aggregate demand).

However, panel studies which were conducted with using a broad base of national data, have ignored specific of national mechanisms for rationing access to goods, such as the role of governmental suggestion of free goods and services, the national rules and regulations of interaction between producers and consumers and many others. In the most abstract form, our idea may be expressed as: to supplement the panel research with studies of household spending patterns in some national circumstances, taking into account the impact of the free offer of goods and government subsidies to households. In addition, we want to try to estimate the impact of specific national institutions that govern individual or collective (in respect of goods, consumption of which are the result of collective choice mechanisms) consumer behavior.

Proposed research may serve as a complement for global panel models (through defining the mechanisms of manifestation the general laws of consumer behavior in certain national conditions) and clarification of "trajectories", "scripts", under which global patterns of consumer behavior appear in certain national economy. For investigation the connection between changes in consumption patterns and levels of household wealth commonly are using practically only two principles.

The first thesis that households with relatively lower income are characterized by relatively lower diversification of consumer spending, primarily because they spend relatively more of their income on food. This thesis was confirmed by numerous empirical studies since classic Engel's works, to a recent models of consumer behavior: the share of expenditure on food (expressed by proportion of expenditure on food to income) tends to decrease with income growth [2, 3, 5, 6].

A second thesis (in work [2] – basic stylized fact): income growth is accompanied by increasing diversification of consumer spending, and a leading role in this process plays reducing the share of expenditure on food. The most radical expression of this thesis was the "strong" wording of Engel's Law, "doubling the income of a typical (representative) household is accompanied by a decline in the share of household expenditure on food by 10 percentage points" [7].

Such diversification is associated with extension of consumer's choice and enhancement well-being of typical subject of demand. For example, in [5] the proverb is quoted that "variety is the spice of life" and growth of consumer's spending diversity is considered like manifestation of economic opportunities extension in consumers behavior.

We propose to use assessment of the real change in amount of consumption and relative prices to determine the "scenario", under which the changes of spending proportion occurs and refine their impact on public welfare. So increase of expenditure on a commodity group may reflect the result of lower its relative prices, accompanied by elastic expansion of demand, as well as the result of relative price increase, in conditions of price inelastic demand on this commodity group. Clearly, these two scenarios will have different effects on the welfare and conditions of reproduction of the human potential of society. Clearly, these two scenarios will have different effects on the welfare and conditions of reproduction of the human potential of society, similar views can be seen in [8].

In turn, in the context of assessing the contribution of a branch in changing of consumer welfare, the combination of reduction in the relative price with elastic expansion in demand may be a result of increasing production capabilities, which ensured the growth of commodity group availability as well as be caused by substitution of higher quality (and expensive) by goods of less quality (and cheaper). The latter result can be provided by changes in structure of import due to changes in the national currency, or by large-scale government programs to support production that diverted resources away from solving other social issues. It is clear that the assessment of social outcomes from the industry in the first, second and third cases will be different.

That is why we consider it useful to create analytical instruments for deeper understanding of the relationship between changes in the structure of consumer spending – on the one hand, and shifts in the level of welfare; distribution of burden and gain from fluctuations in relative prices between social groups; changes in the availability of various goods and services for the "representative" household – on the other.

For that we propose the following direction of development the common approaches [6, 9] to analyzing the structure of consumer spending.

1. Supplement the analysis and modeling of the structure of consumer spending with using share of commodity groups in the consumer budget by analysis with using indexes of real volume of consumption, combined with the localization causes of fluctuations in relative prices by commodity group. The result should create preconditions to clarify the contribution of certain industries and commodity groups in the dynamics of consumer welfare.
2. For the goods categories, have been produced with a large-scale government supplement of private suggestion, we proposed to study the dynamic of real volume of consumption and relative prices, coupled with changes in the principles, objectives, priorities and levers of government policy in coinciding sectors of economy. It should promote to clarify the evaluation of government programs due taking in account the rate of growth consumption and availability of goods and services for different segments of the population.

This article contains only the first attempt to apply described above approaches to study the structure of household expenditures. Clearly insufficient authors experience in conducting researches under recent methodological frame allowed them to build only initial variant of statistical database and tools for modeling. Our mathematics tools and structure of this database doesn't allow yet obtain a complete solution of formulated above problems. However, we hope that even this issue, made with very simplified analytical tools, may substantiate perspective of the proposed direction, and notice from our more experienced colleagues will help us to improve research tools.

In the article we will try to explain the changes in the consumption pattern of households based on the "canonical" idea about the dominantly influence of two factors: the total level of spending and relative prices. We also try to show the limitations of this explanation and offer first step to specify the causes of fluctuations in real amount of consumption of some goods categories – not only as a result of consumer choice, but in the context of consumer interaction with manufacturers and impact of government programs and regulatory frames.

3. Methods

We proposed for modeling quite simple linear additive function, the first element of which is close to Working function, and the second – a very simplified replacement of Theil proposed mathematical tools for incorporating relative prices into mentioned model [7]. Suggested approaches to modeling are differ by using cumulative rate of growth amount of consumption as the dependent and cumulative rate of growth total spending and relative price as explanatory variables. The dependent variable Y_i – cumulative growth rate of amount of consumption for goods category i; explanatory variables X_1 – cumulative growth rate of real total consumption spending; X_{2i} – cumulative growth rate of relative prices for the goods category i.

This function is expressed as:

$$Y_i = a_0 + a_1 * X_1 + a_2 * X_2, \tag{1}$$

where a_0 – absolute term in function, expresses growth rate of consumption of goods category "i" which are independent from factors involved in function; a_1 – coefficient of variable "cumulative growth rate of real total consumption spending", reflects marginal growth of quantity consumed of goods category "i" in response to growth total spending; a_2 – coefficient of variable "cumulative growth rate of relative prices for the goods category "i", reflects marginal growth of quantity consumed of goods category "i" in response to growth this goods category relative price.

For such database the first order derivative is annual mean growth rate of quantity consumed of goods category "i" during the retrospective period. The partial derivative by first explaining variable is annual mean growth rate of quantity consumed of goods category "i", caused by changing of real total consumption spending. The partial derivative by second explaining variable is annual mean growth rate of quantity consumed of goods category "i", caused by changing of relative price that goods category.

We used growth rate of total consumption expenditures but not their absolute size as the first explanatory variable, then logarithmic (traditional for such models) form of expression aggregate spending in function is not used.

Estimation of model parameters was obtained by first method of least squares (1LSM).

Matrix of estimates of model parameters was determined based on the equation [10]:

$$A = (X^T X)^{-1} X^T Y, \tag{2}$$

where X – matrix of explaining variables; X^T – transposed matrix of explaining variables; Y – matrix of dependent variables.

For estimating the own price elasticity and total consumer spending elasticity we have calculated the corresponding coefficients for all commodity categories.

For this, we used the following formula:

$$E_i = \frac{a_i * x_i}{Y_i},$$

where E_i – explaining variable “i” elasticity of dependent variable; x – average (geometric mean) value of explaining variable; Y – average (geometric mean) value of dependent variable.

The initial data was obtained on the official website of the State Statistics Service of Ukraine [11].

Ukrainian households’ consumption spending were used as an initial characteristic for database formation. Such indicators reflect the average (over the year and across all Ukrainian households) size of consumption spending in monthly dimension per household [12]. So, the one observation (one position in the dynamic series) – is the average monthly expenditures of Ukrainian household for a certain commodity for a certain year. To build the database, all nominal indicators are calculated in real dimension using aggregate consumer price indices (the price indices for each commodity group were used [13]). In the next step, to form the model database, all absolute real indicators were recalculated into base growth rates (2005 was used as the base year). As a result, the dynamics series, used for modeling characterize relative changes, that occurred during the retrospective compared with 2005: 1) the real size of consumption spending on a certain commodity; 2) relative prices of a certain commodity; 3) the total size of consumer expenditures of households;

The retrospective period is limited to 2017 for a number of reasons. First, by striving to ensure the correctness of data comparison with research, which is chosen as a basis for comparison [1]. Secondly, by the necessity to ensure qualitative homogeneity of the series of dynamics. We take into consideration that since 2019 the method of forming sample population for conducting sample surveys of the households’ living conditions, which serve as a source of data for the [12], was updated.

4. Results

The calculation results for the major (by share in consumption spending) goods categories are shown in table 1.

The small number of observation (only 12 for each commodity category) does not allow as consider modeling results as reliable. But if the low reliability is caused only by insufficient number of observations such problem may be simply eliminated in our farther researches.

All calculated functions show relatively high significance of estimated parameters. In particular, the determination coefficients are ranged from 0.616 (for alcohol and tobacco) to 0.978 (for health care), while for five of the eight commodity categories R^2 size exceeds the value of 0.9. For all product categories except one value of Fisher factor is higher than critical (tabulated point).

For example, the determination coefficient of function food real quantity consumed dependence on total spending and relative price indicate that up to 97% variation of dependent variable is determined by the variation of factor variables and the value of Fischer factor (114.84) is much higher than critical, which allow consider the coefficient of determination as not random. Value of Durbin-Watson test (1.8, i.e. in the range from 1.5 to 2.5) allows accept the hypothesis of no autocorrelation of deviations, and the size of t-test for all parameters of model indicates the significance of their differences from zero.

Six of the eight functions have “classic” signs of parameters: positive under the growth rate of real consumption spending and negative – under the growth rate of relative price. Two functions (clothing and footwear and healthcare) have negative coefficients at both explaining variables, and significance of parameter at total spending in function of clothing and footwear quantity consumed is low (the standard deviation exceeds the parameter value more than 17 times – table 1).

This negative sign of coefficient on the variable “growth rate of real total consumption spending” is predetermined by specificity data for 2014 – 2015 years, where the dynamics of real total consumer expenditure has become a pronounced negative, but the quantity of clothing and

Table 1. Parameters estimated and their significance for eight commodity categories which have greatest specific weight in consumption budget of Ukrainian households.

Commodity group	Food	Housing, water, electricity, gas and other fuels	Clothing and footwear	Healthcare*	Alcoholic beverages, tobacco	Transport	Communication	Furnishings, household equipment and routine maintenance of the house
Share of commodity category 2015, %	53.1	14.6	7.6	4.0	3.8	3.8	2.8	2.3
a_0	158.236	101.187	485.3754	130.781	42.1761	-1.609	485.77	86.871
Standard error	21.745	13.220	61.4530	20.3725	29.2058	36.351	85.776	86.087
t_{a_0}	7.28 ($> t_{tab}$)	7.654 ($> t_{tab}$)	7.898 ($> t_{tab}$)	6.420 ($> t_{tab}$)	1.444 ($< t_{tab}$)	0.044 ($< t_{tab}$)	5.663 ($> t_{tab}$)	1.009 ($< t_{tab}$)
a_1	0.792	0.211	-0.0238	-0.05886	0.697474	1.45153	0.354149	1.084
Standard error	0.052	0.082	0.4063	0.178893	0.209410	0.2021	0.608456	0.395
t_{a_1}	15.15 ($> t_{tab}$)	2.566 ($> t_{tab}$)	0.059 ($< t_{tab}$)	0.329 ($< t_{tab}$)	3.331 ($> t_{tab}$)	7.182 ($> t_{tab}$)	0.582 ($< t_{tab}$)	2.747 ($> t_{tab}$)
a_2	-1.420	-0.227	-4.4972	-0.11353	-0.1017053	-0.27967	-4.54763	-0.876
Standard error	0.240	0.035	0.4350	0.00736	0.1444918	0.202123	0.513060	0.755
t_{a_2}	5.92 ($> t_{tab}$)	6.460 ($> t_{tab}$)	10.339 ($> t_{tab}$)	15.425 ($> t_{tab}$)	0.704 ($< t_{tab}$)	1.384 ($< t_{tab}$)	8.864 ($> t_{tab}$)	1.161 ($< t_{tab}$)
R^2	0.970	0.904	0.9412	0.978067	0.615724	0.886838	0.920996	0.676
F	114.842	33.052	56.0721	156.0754	5.608034	27.429	40.80171	7.295
DW	1.8	1.696	1.186	1.941	1.741	1.172	0.008	1.712

* – Note, that methodology of Ukrainian statistic does not take in account the public spending on health and education, that does not allow to compare domestic Ukrainian data with data ICP.

footwear consumed continued to grow quite steadily. Thus, during 8 years out of 10 included in the database, the size of the real total consumption expenditure and quantity of clothing and footwear consumed showed a kindred trend, and only a sharp distinction in 2014 – 2015 caused the negative sign of coefficient at total spending variable.

The trend in real quantity of consumption commodity category "Healthcare" was mainly formed by events of 2008. In conditions of rising real total consumer spending and a radical increase in the relative price of this commodity group (since 92% of the 2005 level till 822.3%) occurred falling quantity of consumption this goods category since 120% of 2005 till 17.36%. After this the scale of consumption this commodity category remained weakly sensitive to fluctuations in total consumer spending and relative prices.

Such a rapid rise of relative prices and falling of quantity "healthcare" consumed forced us to seek an explanation primarily in the methodology of obtaining source database, particularly in procedures of assessment prices and quantity consumed of medical services. Such searches could be subject to further researches on the structure of Ukrainian households' expenditures.

The high total expenditure and own price elasticity of real quantity food consumed (table 2) indicates that consumption patterns of Ukrainian household are the same with the low-income countries. The first (high spending elasticity) directly indicates a low level of satisfaction even the basic needs of Ukrainian households and as a result – minimal opportunities for households to allocate own resources on consumption of commodity groups, which are more related with improving the educational level and health care quality, increasing of access to modern communications and integration into the mechanisms of social interaction.

Table 2. Spending and own price elasticity for eight prominent commodity categories in total spending of Ukrainian household.

Commodity group	Spending elasticity	Own price elasticity
Food	0.842	-1.202
Clothing and footwear	1.173	-0.623
Furnishings, household equipment and routine maintenance of the house	0.839	-0.376
Housing, water, electricity, gas and other fuels	0.288	-0.395
Health	-0.282	-2.570
Transport	1.254	-0.236
Alcoholic beverages, tobacco	0.737	-0.094
Communication	0.180	-1.074

Second (significant own price elasticity) indicates high households vulnerability on fluctuations in relative prices and incomes. Even minimal adverse changes in market conditions, or deprivation from government programs of social assistance lead to significant threat for an acceptable lifestyle, for ability to improve own social status.

According to the coefficients of income (total spending) elasticity of consumption obtained in our article we have the following classification of commodity categories by the reaction on the growth of consumers' income (table 3).

Table 3. Classification of researched commodity category by total spending elasticity.

Commodity group	Luxuries / essentials / low quality
Food	essentials
Clothing and footwear	luxuries
Furnishings, household equipment and routine maintenance of the house	essentials
Housing, water, electricity, gas and other fuels	essentials
Healthcare	low quality
Transport	luxuries
Alcoholic beverages, tobacco	essentials
Communication	essentials

5. Discussion

We tried to compare our results with estimates of the income and own price elasticity of Ukrainian households demand which were obtained in the survey, which authors have used to model the panel database on ICP data [1]. The elasticity of demand calculated by our model and derived in work are brought together in table 4.

Table 4. Spending and own price elasticity of spending shares (in [1]) and growth rates of quantity consumed (in our work) observed for Ukrainian households.

Commodity group	Our work				Seal and Regmi [1]			
	Spending elasticity		Own price elasticity		Spending elasticity		Own price elasticity	
	Rank by absolute value of coefficient	Coefficient relatively to elasticity for food	Rank by absolute value of coefficient	Coefficient relatively to elasticity for food	Rank by absolute value of coefficient	Coefficient relatively to elasticity for food	Rank by absolute value of coefficient	Coefficient relatively to elasticity for food
Food	3	1.00	2	1.00	7	1.00	7	1.00
Clothing and footwear	2	1.39	4	0.52	6	1.30	6	1.66
Furnishings, household equipment and routine maintenance of the house	4	1.00	6	0.31	5	1.76	2	2.22
Housing, water, electricity, gas and other fuels	6	0.34	5	0.33	2	1.83	5	2.10
Healthcare	8	-0.34	1	2.14	1	2.17	1	2.68
Transport and Communication	6	0.58	4	0.69	3	1.80	3	2.15

It is clear that comparability of coefficients, which we drawn together, is very limited for many reasons. First, the obvious imperfection of mathematical tools of our model and insufficiency of its statistical base (it includes observations only for 11 years).

Second, the differences between expenditure categories used in studies of international consumption patterns and structure of consumption spending using by Ukrainian statistics.

In particular, "alcoholic beverages and tobacco products" included in the commodity category "Food" for the international methodology and highlighted in a separate category for Ukrainian national statistics. As a result, we can expect that the estimate of spending and price elasticity of demand for food by the Ukrainian statistics will be lower than the similar estimate conducted by data, taking into account alcohol and tobacco as part of food. Transport and Communication are accounting separately in inner Ukrainian statistic and united in to one commodity category in database of [1].

Thirdly the differences in the way of accounting spending on education and healthcare make indicators of Ukrainian internal statistic for these commodity categories absolutely no comparability with ICP data (inner Ukrainian statistic does not account individual consumption financed by government, which constitutes the main part of such goods consumed).

Finally, forth, differences of dependent parameters used in the studies: the share of expenditure on a commodity category – in [1] and the growth rate of consumed quantity – in our work.

If the last cause may be eliminated easy (by dividing our elasticity coefficients to growth rate of total expenditures for the retrospective period and multiplying them by index of relative price for each commodity category) the first three reasons are not amenable to correction within available for authors methods.

Taking into account all differences between the databases used for the calculation of the elasticity in our study and in the [1], it seems more correct to compare not the size elasticities, but their ratio (rank of category's elasticity among all calculated and ratio of category's elasticity to food elasticity, which was selected as the basis for comparison). Therefore mentioned figures are showed in the table 4.

Among calculated [1], three types of own price elasticity we consider as closer to our calculations is Slutsky own price elasticity (because they as our reflect the impact of price changes under conditions of fixed real income when Cournot own price elasticity provide a constant nominal income, respectively – on the basis of real is changed).

The spending elasticity of food, estimated by our model not lower as expected, but higher than in the study, which have been using integrated data on the demand for food, alcohol and tobacco and have third rank instead seven in [1].

Such a difference can be explained by the specific dynamics of the Ukrainian households' economic well-being in the period 2009-2014 and, accordingly, by the characteristics of the food demand income elasticity. As shown in [14], the high propensity of Ukrainian households to spend additional income on food is caused by long-term stagnation of economic well-being and even negative dynamics of consumer spending during the crisis (2008-2009) and the first post-crisis years. The authors [15], using the tools of Engel's curves, prove that Ukrainian households are at the initial stage of the evolution of the consumer expenditure structure. And that causes serious problems and limitations regarding the development of the social sphere: as long as the demand for food products remains highly elastic on income, such fields as education and healthcare have minimal chances on the expansion of non-budgetary financing. Accordingly, the development of the policy of reforming the leading branches of the social sphere should be based on analytical support for defining the expected growth of households' consumer spending and an assessment of the prospects for overcoming the exclusive role of budgetary financing of the social sphere. Our and further researches on the dynamics and structure of households' consumer spending can serve to clarify such an assessment.

Consumption of clothing and footwear responses to changing total spending as "luxuries" by our data, instead expected "necessities" – total spending elasticity coefficient is significantly higher than units and have second rank instead sixth in [1].

The spending elasticity of "Furnishings, household equipment and routine maintenance of the house", obtained in our research lead to different classification this commodity category between "luxuries" / "necessities" in comparison the results of study [1].

Assessments of spending elasticity for "Housing, water, electric energy, gas and other fuels" obtained in our study and in [1] also have significant differences: consumption responses to shifts in spending as "necessity" by our results and as "luxury" – by [1].

The spending elasticity of quantity consumed for commodity category "transport and communication" was calculated in our study as weighted by share in overall spending average of two elasticity indicators: for Transport and Communication. And our assessment of spending elasticity for this commodity category indicates that quantity consumed respond to changes in total spending as necessity which is significantly different from [1] results.

Indicators of own price elasticity by our calculations also differ significantly from the parameters calculated in [1]. Only concerning to Housing, water, electricity, gas and other fuels; Healthcare; Transport and Communication the ranks by coefficients of price elasticity, calculated in both studies are close to each other.

For five commodity categories, we also compared the actual indices of real changes in quantity of consumption with similar indicators, which were calculated on basis the elasticity coefficients, obtained in our and [1] models (table 5).

Elasticity coefficients are designed [1] for "Food" and "Furnishings, household equipment and routine maintenance of the house" have demonstrated quite good explanatory power. But estimated figures for both models clearly deviate from the actual values, which were observed for clothing and footwear, as well as for Housing, water, electricity, gas and other fuels.

Namely in explaining such deviations of actual fluctuations in quantity of consumption in comparison of the figures, calculated on basis of formal models, which are accounting impact of

Table 5. Comparing actual and estimated growth rate of quantity consumed for main commodity categories in consumption basket of Ukrainian households.

Commodity group	Growth rate of quantity consumed		
	Actual 2015/2005 ×100-100, (%)	Calculated on basis elasticity coefficients, obtained in our and Seal and Regmi [1] researches	
		Our model	Seal and Regmi
Food	3.952	8.702	3.710
Clothing and footwear	202.329	39.425	42.197
Furnishings, household equipment and routine maintenance of the house	33.974	15.564	35.947
Housing, water, electricity, gas and other fuels	-31.659	-57.288	-123.573
Transport and Communication	183.164	31.712	34.794

total spending and relative price, we see the direction of farther researches.

For example, to explain the actual respond of amount of consumptions to fluctuations in the total costs and relative prices by commodity category “Housing, water, electricity, gas and other fuels” we need to consider the following determinants of the system of interaction between producers and consumers of such goods.

First, majority of consumers housing services (like house heating, water supply and sewage and other) simply have no impact on their consumption (due to lack of maintenance for personal accounting of the quantity of consumption and extremely flawed accounting system of collective consumption).

Second, that the regional monopoly suppliers of these goods, both commercial and public enterprises receive the greater benefits (in the form of official income and informal income, which can reach a large part of the officials), the more consumption is recorded by imperfect system of accounting. Under such enterprises the spreading of individual metering and regulating consumption’s scope is just blocked and transition from collective to individual account of the scale of consumption has faced with strongly sabotage.

Third, the mechanisms of collective consumption in Ukraine is almost absent: Ukrainian consumers are currently unable to identify, formulate and defend their collective interests, both because of the shortcomings of the institutional framework and through the specificity of the technological conditions (e.g. collective consumption of services of gas supply in homes, numbering thousands of apartments where the most number of participants makes coordination extremely difficult) and due to the lack of experience and traditions of activity for upholding the collective interests of consumers.

A calculations made in the [1] and many other studies consist estimating of the demand elasticity by income, which have been conducted on base of panel database (i.e. no aimed to revealing the demand dependence on the dynamics of income over time) or time series, which show clearly dominating trends of increasing consumers’ economic opportunities. Cases where the structure of consumer expenditures is formed in a long-term stagnation or even decline of real income and spending fortunately are rare in today’s world.

However, the mechanisms of consumer behavior adaptation to reduce the real purchasing power of households could not, in our opinion, be considered as symmetric mirroring of the adaptation to revenue growth. We believe that among the commodities, classified to the same group (essentials or luxuries) on the basis of reaction on spending growth we might find goods with radically different reaction to the reduction of income.

Such differences could be caused by a peculiar of "ratchet effect" for different commodities groups: the amount of consumption some goods reduces through a decline in income slower, but some goods – rapidly than increases in response to analogous by absolute size growth of households spending. Motives of consumers could be related with desire to save external features of lifestyle reached in times with higher income, keep the access to sources of social mobility, maintain social identity and ability to communicate with humans who receive higher income.

6. Conclusions

1. Shifts in the structure of households' consumer expenditures in themselves are primary insufficient to definitely assessment of consumers' welfare, caused by such changes (if we don't consider reducing of food share or diversification of consumption spending). To create the conditions for such assessment we propose to complement the data on the dynamics of the structure of households' spending by information about changes in amount of consumption and relative prices for aggregated product categories. It will allow to use the structure of households' spending not only for detection consumer preferences and patterns of demand, but also to assess changes in households' capacity to meet their needs, and for estimating the economic burden, imposed on consumers in the process of interaction with the manufacture of various commodity categories.
2. In today's world, fortunately we not often can found time series of nationwide statistics that demonstrate the dynamics of consumer spending in condition of long-term significant reduction of households' real income. We believe that the patterns, which were confirmed empirically on the basis of databases, covering periods of rising the households' economic opportunities, have little explanatory power for spending structure, formed amidst reduction of consumers' real income. The clarifying of patterns, which determine the national consumption adaptation to reducing the average real households' income, in our opinion, is a promising direction for future research. Empirical basis for such research is provided by statistic on consumption spending of Ukrainian households in 2005 – 20015 years, which was primary analyzed in this paper.
3. Such analysis have shown that even for commodity groups traditionally classified as essentials with a relatively high income elasticity may be observed particular response to the reduction in real income, which cannot be explained by mechanical application of traditional demand models. For example, Ukrainian household expenditures on commodity category "Clothing and footwear" increased by a decline in real incomes, although the opposite reaction is expected by traditional models.
4. We obtain empirical proof in favor of the thesis that the development of the policy of reforming the education and healthcare resource provision should be based on analytical support for defining the expected growth of households' consumer spending and an assessment of the prospects for overcoming the exclusive role of budgetary financing of the social sphere. The further researches on the dynamics and structure of households' consumer spending can serve to clarify such an assessment.

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Complex socio-economic solutions regarding the sustainable ecological development of the Ukraine regions

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Abstract. The article presents the current state of the ecological and socio-economic development of Ukraine and its regions, the consequences of hostilities on the territory of Ukraine and, as a consequence, the trends of damage to the surface layer of soils, pollution of the atmospheric air, and the subsoil of Ukraine with heavy metals and other harmful substances. The authors emphasize the socio-economic realities and potential trends of social security for internally displaced persons who were forced to leave their place of residence due to hostilities. Based on the analysis of potential total losses in the regions of Ukraine, a complex of socio-economic solutions is provided for strengthening the sustainable economic and ecological development of its regions. Attention was drawn to the fact that the main environmental problem of Ukraine for the coming decades will remain the problem of demining a large part of the territory. On the basis of the factorization of the given trends, the definition of catalysts of ecological development is proposed, which should signal the need for additional specialized research. It is concluded that despite the importance of solving environmental problems and the catastrophic consequences of hostilities for the surrounding environment, the social component and its economic support are fundamental in the processes of "regeneration" of the normal life activity of the regions.

1. Introduction

Sustainable economic and ecological development of Ukraine and its regions depends on Ukraine's natural resources, their economical use, preservation and protection of the environment. However, as of 2023, under conditions of full-scale war and hostilities, about 1.2 million tons of pollutants have already entered the atmosphere, including 430 thousand tons of carbon monoxide, 700 thousand tons of dust, 40 thousand tons of light organic compounds, significant amount of heavy metals and other harmful substances [1]. The consequences of these emissions turned out to be catastrophic and have already reached almost \$ 4.2 billion: 1.8 billion is damage from forest fires, \$ 1.6 billion – from grass fires and \$ 52 million from burning oil and oil products. And these sums do not yet take into account the direct damages caused by the explosion of the Kakhovka Hydroelectric Power Plant in the Kherson region. In addition, due to the damaged objects of the housing stock, communal and transport infrastructure, polluting substances were additionally emitted into the atmospheric air, which brought losses of more than $ 1 billion. In large areas of Ukraine, the surface layer of the soil was significantly damaged as a result of the construction of fortifications, explosions, burning of ammunition, military maneuvers, etc. In other words, 186,000 km^2 of land were contaminated, which is almost 31 % of the territory of Ukraine. Among them more than 20,000 km^2 were damaged more than 75 %. In a full-scale war, Russia makes massive use of so-called dragon's teeth – defensive structures in the form of concrete cones, lined up to stop light vehicles and hinder the advance of infantry, and fills trenches with concrete. Such fortifications appeared in most territories of the temporarily occupied regions of Ukraine [2]. Similar structures were used during the Second World War, so removing the dragon's teeth turned out to be economically impractical at the time. That is, it means that they can remain in their places.

The territories of Donetsk, Kharkiv and Zaporizhzhia regions suffered the most damage, not including the territories of Luhansk region, which is mostly under occupation. In total, total damage from land damage and soil disturbance is estimated at 9.8 billion dollars, endangering the use of damaged land and requiring reclamation, demining, and demining. The estimated amount of damages due to the destruction of the Kakhovka Hydroelectric Power Plant exceeds UAH 55 billion, however, the recording and analysis of direct damages and environmental consequences caused by this tragedy continues, as do the military actions on the territory of Ukraine, and specialists of various Ukrainian and international organizations are involved in this.

In addition to this should be added the losses suffered by the regions and the state from the forced external and internal migration of the population. Millions of Ukrainians left their homes, both in regions where hostilities continued or are continuing, and in those where hostilities did not take place. A significant part left abroad, but accurate statistics on the number, age and gender composition of forced migrants have not been compiled for various objective and subjective reasons. Official statistics claim that only about 2.5 million people were registered as internally displaced persons (IDPs) [3]. And the majority of people who settled with their relatives in other regions quite often do not register as IDPs, hoping for a quick return. However, as international experience shows, the longer the conditions for return are absent, the fewer people will return to their previous place of residence if such conditions arise. Therefore, it can be assumed with high probability that a significant part of those who went abroad or registered as IDPs at their new place of residence may not return to the places from which they left, and this will significantly affect the resettlement system in Ukraine and the placement of productive forces in the regions of Ukraine.

Therefore, it is quite problematic to determine and finally predict the consequences of total losses by region. However, it is already possible to envisage a set of socio-economic solutions to strengthen the sustainable economic and ecological development of Ukraine's regions.

2. Literature review

Decisions made today regarding sustainable economic development are not new for Ukraine. Many scientific works on economic growth and economic development are devoted to this topic [4–6]. These are also topics related to the need for continuous growth and ensuring the scale of consumption of natural resources [7–9] in peacetime and wartime, as well as post-war recovery and use of natural resources [10]. However, the war continues and the situation with planning for sustainable economic development and the use and access to available resources is worsening. Therefore, there is a need to develop complex socio-economic solutions for sustainable ecological development, taking into account all aspects of the restoration of industrial activity and social life in the liberated territories, restoration, relocation, repurposing and diversification of business in all regions of Ukraine.

Therefore, the main goal of the research is the identification of modern environmental challenges and the determination of strategic directions for the implementation of complex socio-economic solutions, taking into account the ecological components of a safe environment.

3. Methodology

The basis of the research methodology is the analysis of the current state of the sustainable development concept implementation in Ukraine and in the world, which originated in the 1970s, developed under the influence of global trends and identified problems, the main of which are environmental challenges, poverty alleviation, food security, equal rights and opportunities for all members of society.

The 17 sustainable development goals that were approved during the 70th anniversary session of the UN General Assembly in 2015 at the Sustainable Development Summit were in the focus of attention within the framework of this concept. According to the resolution of the summit, most of the goals should be implemented by 2030, but the current global cataclysms call this deadline into question. During the research, it was found that depending on the circumstances, the order and priority of goal implementation may not match.

Among the methods of scientific knowledge that were used, it is possible to note: analysis (to identify modern modifications of the concept of sustainable development in the regions of Ukraine), induction (to form conclusions regarding the priority of actions regarding complex socio-economic and environmental solutions); statistical analysis (to highlight quantitative indicators regarding the current situation in the regions of Ukraine); comparison (to compare the goals of sustainable development in Ukraine and in the world).

4. Results

In order to form complex socio-economic solutions, it is necessary to have a complete and sufficiently reliable assessment of the socio-economic and ecological situation in the country. However, none of the existing assessments made by various international and domestic agencies [1–3, 10] can form a sufficiently realistic picture of the ecological situation in the country. Based on this, it is quite difficult to make any predictions for the future. Although, thanks to the conducted research, it is possible to identify the main problems in monitoring the state of the regions, in obtaining certain information about pain points and sensitive zones, as well as priorities in assessing the ecological state.

The main environmental problem of Ukraine for the coming decades, regardless of when the war ends, will remain the problem of demining a large part of the territory. Today, Ukraine is the country whose territory is the most mined in the world. Luhansk, Donetsk, Zaporizhzhia, and Kherson regions are almost completely mined. Mykolaiv, Kharkiv, Sumy, Chernihiv, Kyiv, and Zhytomyr regions remain partially mined. About a fifth of the country's land area is currently considered dangerous. Currently, it is not possible to estimate the amount of mining of the sea coastal areas and the water areas of the Black and Azov seas in general [11].

Environmental problems caused by full-scale hostilities directly affect the socio-economic situation of the regions. In particular, a bright indicator is the export of goods by region of the country. In recent years, before the start of the full-scale invasion, Ukraine was considered an export-oriented country. In 2022, a significant decrease in exports was recorded in 16 regions, compared to 2021 figure 1.

The main reasons for the reduction of export products: inability to carry out production due to the presence of explosive objects; destruction of production facilities; disruption of logistics channels. The largest decrease in exports was recorded in the Donetsk, Luhansk, and Kherson regions, where the decrease over the year took place by 85-95 %.

The impossibility of carrying out economic activities at the pre-war level led to a reduction of income in the budgets of local communities. Donetsk, Luhansk and Kherson regions also suffered the greatest losses. Revenues to the local budgets of these regions in 2022, respectively, amounted to 35.5 %; 50.9 %; 31.2 % of the indicators of 2021. In general, a reduction in local budget revenues was recorded in all regions of the country, with the exception of Zhytomyr and Lviv regions [12] (figure 2).

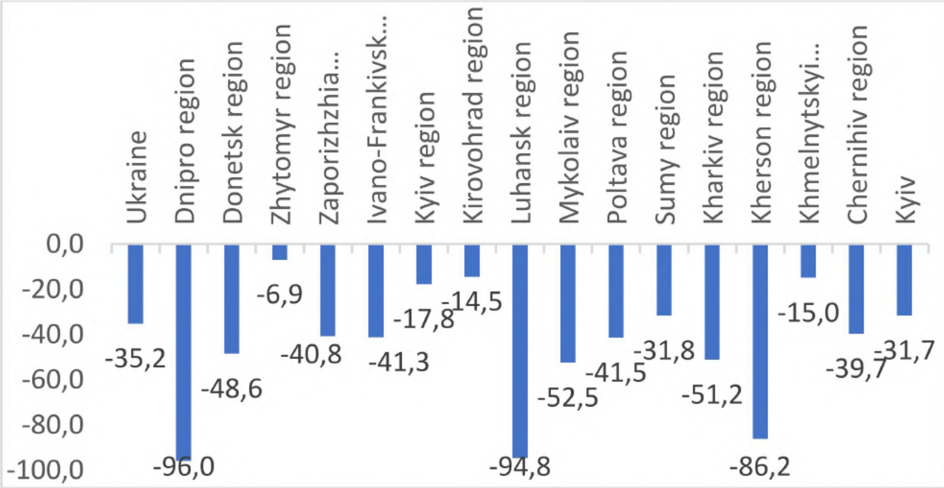

Figure 1. The level of reduction in commodity exports by regions of Ukraine 2022/2021, % [12].

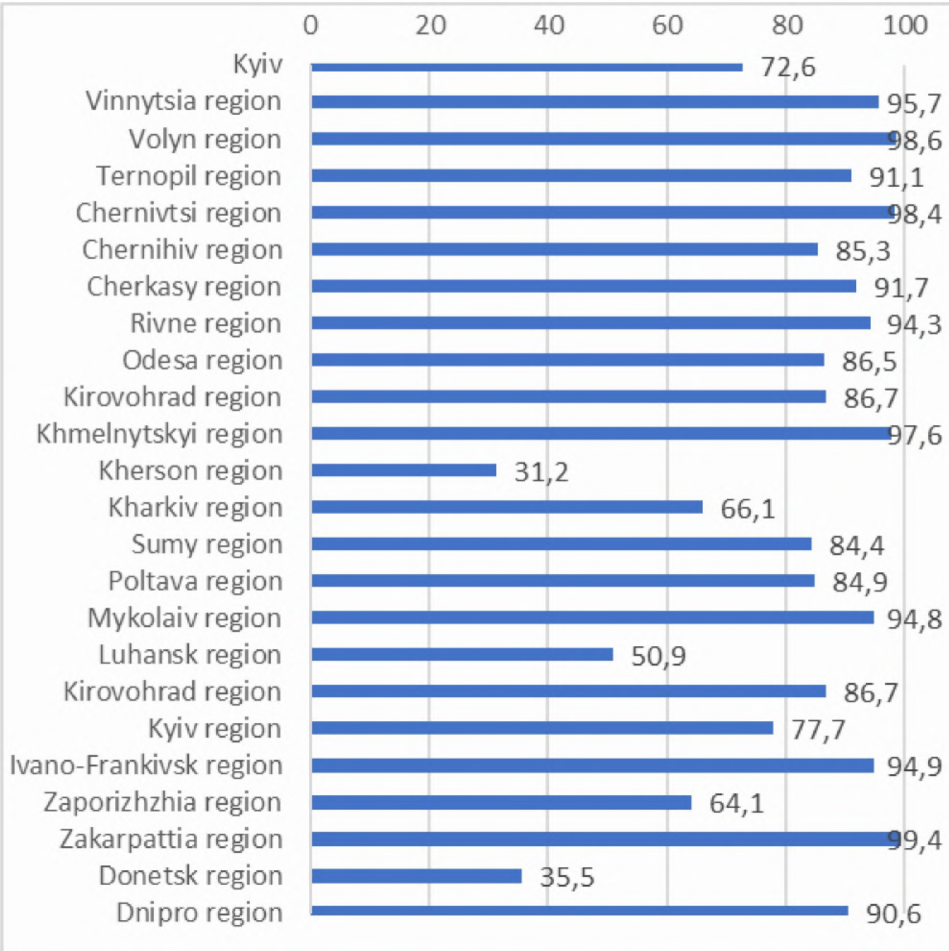

Figure 2. Dynamics of revenues to local budgets of territorial communities 2022/2021, % [12].

Most of these assessments will be very difficult to carry out in the conditions of martial law in some regions of the country, but after the end of hostilities, it will be necessary to make the most complex socio-economic decisions regarding sustainable ecological development, which we must already talk about now, namely:

1. Monitoring of the state of the environment, ecological consequences of individual territories through the prism of the expected post-war restoration and reconstruction of production.
2. Development of forecasts and scenarios for the future development of regions on the basis of cooperation models integrated into the European Union. For this purpose, it is possible to invite authoritative European experts, organizations for assessment and ensuring ecological balance in the regions.
3. Creation of platforms for verification, processing, documentation and identification of a large amount of data on the direct and indirect effects of military actions on the environment based on those regions that received the greatest negative consequences. On the basis of such consolidated information, it is possible to hold various kinds of debates regarding the correction of subsequent decisions at the national, international, including European levels.
4. Determination of the catalysts of ecological development, which should signal the need for additional research, and if necessary, to change, adjust or fundamentally revise the set of socio-economic solutions for the sustainable development of regions.
5. Dissemination and distribution of the received results of the assessment of the state of the environment in order to ensure effective communication with stakeholders and other target audiences.

The identified measures will allow identifying critical gaps in environmental information regarding the sustainable development of regions, implemented socio-economic measures, and the existing capabilities of regions to independently eliminate recognized problems; to find the right priorities in environmental protection and to give answers to the public reaction and various multidimensional connections that arise between the territorial community and the environment.

Today, business remains the backbone of sustainable socio-economic and environmental development in the country. According to the results of a survey [13] of the European Business Association, 96 % of businesses that continue to operate adhere to the goals of sustainable development and strive to implement them. This indicator coincides with the pre-war level recorded in 2021. At the same time, according to the results of an expert study of the level of integration of the UN sustainable development goals into the strategy of business structures and into regional and national strategies, this integral indicator improved by 0.23 points and at the beginning of 2023 amounted to 3.5 points (out of a maximum of 5). The contribution of business to the implementation of the goals of sustainable development was assessed by experts at the level of 3.79 (out of a maximum of 5).

Despite the importance of solving environmental problems and the catastrophic consequences of war for the environment, the social component is fundamental in the processes of regeneration of the normal life activity of the regions. 97 % of working business owners (according to the results of the same survey [12]) note that the main efforts are made to preserve human capital: helping employees and their family members in the process of relocation; timely payment of wages (even in case of temporary downtime of production); financial support for workers and their families affected by hostilities.

This approach is well-founded, because the preservation of human capital will allow the process of ecological and economic recovery of the regions to be launched. Moreover, it is necessary to pay attention to the fact that in each case the priority of tasks of a social, ecological and economic nature will be determined depending on the state of each component of a specific territory (region).

Considering this context, it is possible to present the modern view of the sustainable development concept for the current situation in the Ukraine regions (figure 3).

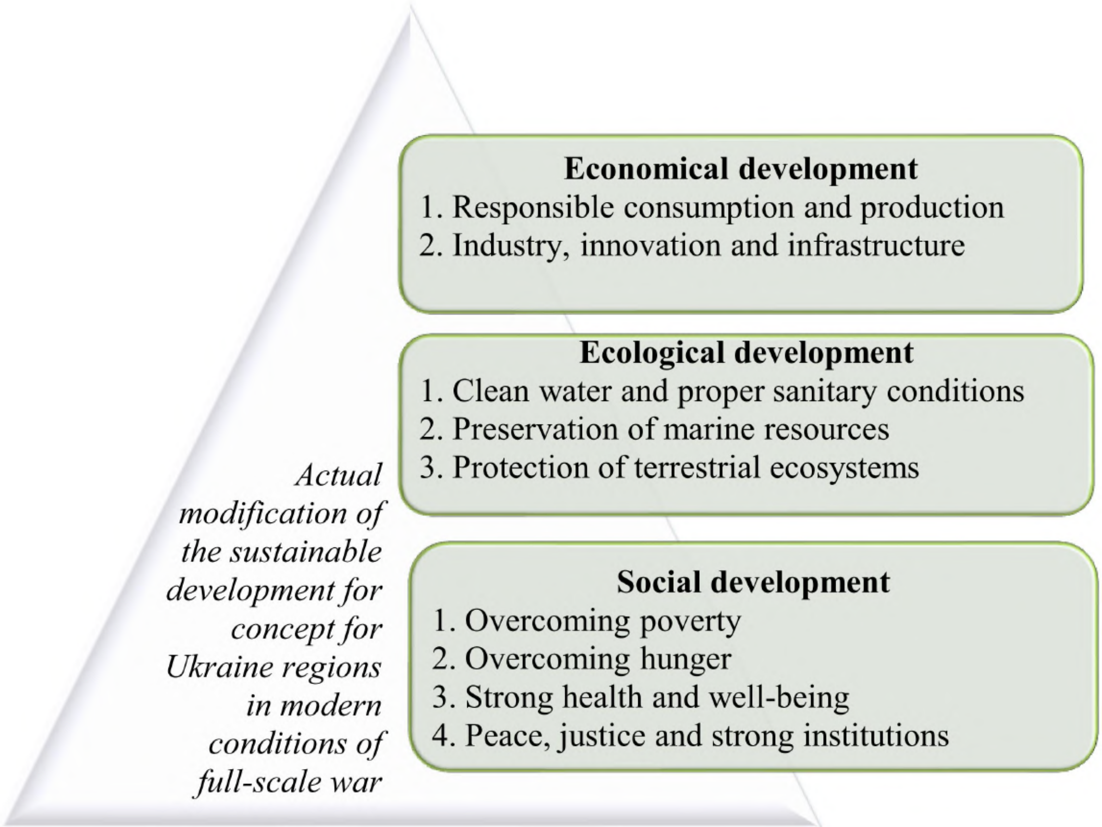

Figure 3. Modern view of the sustainable development concept for the current situation in the Ukraine regions (developed by the authors).

The presented modification of the concept is already being actively implemented in the regions of Ukraine: it is the social component with the main problems that comes first: surviving in war conditions (including evacuation to safer regions), providing all those in need with food and an appropriate level of medical care service. The fourth goal of social development (peace, justice, and strong institutions) is the ideal state that our society strives to achieve. The ecological component is superimposed on the social one: providing the population with proper sanitary living conditions and restoration of territories affected by hostilities (mining, first of all). The economic goals of sustainable development are superimposed as a "third layer", because under the existing conditions, their implementation in the regions of Ukraine is possible only when the goals of social and environmental development are achieved.

Depending on the situation observed in each individual region, the modification of the concept may change. Where the ecological consequences are catastrophic (regions where the evacuation of the population is still ongoing, and the territory has suffered significant losses of natural and recreational resources due to the attacks of the aggressor country), after the end of hostilities, the ecological goals of sustainable development will come to the fore, because in some territories before the return of the local population, it is necessary to carry out a process of complete demining and restoration of critical infrastructure to ensure the minimum household needs of the population.

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A comparison of current goals of regional development in Ukraine and in the world shows discrepancies (figure 4).

Priority goals of sustainable development of Ukraine

Priority goals of sustainable development in the world

Figure 4. Disposition of modern goals of sustainable development for Ukraine at the national and global level, as of 2022 [13, 14].

Based on the identified priority goals of sustainable development (figure 4) and the proposed modification of the sustainable development concept, relevant for Ukraine (figure 3), it is possible to formulate strategic directions of socio-economic development that will contribute to the "reanimation" of the country's ecology during the post-war reconstruction period:

1. Development of renewable energy and implementation of autonomous energy systems based on "green" technologies. Two years of war demonstrated the obsolescence and instability of centralized life support systems. The enemy's targeted strikes on nuclear power plants, hydroelectric power stations, and thermal power plants led to significant losses of capacities at this economy sector and caused "blackouts" of territories under constant shelling. In part, the problem is solved by buying generators for businesses, but most of the existing equipment runs on substances harmful to the environment (gasoline, diesel fuel, etc.).
2. Greening of all economy spheres. Significant losses in the industrial sector set ambitious tasks for the restoration of production, but most large enterprises worked with outdated technologies dangerous for the environment, so the restoration should not take place according to the principle of "modernizing the old" but "building new", safe for workers and the local community, for future consumers of products, etc.
3. Determination (search for new) strategic spheres of ecologically safe economic activity for each region in Ukraine for sustainable socio-economic and neutral ecological development. The most promising is already mentioned the renewable energy sector, which is showing rapid growth at the global level, generating a large number of jobs. Among the most relevant areas, which are already attracting the attention of foreign investors: IT, construction, logistics, the financial sector, medicine.

5. Conclusions

Taking into account the above research results, it can be concluded that the basis for the identification of modern environmental challenges and the determination of strategic directions for the implementation of complex socio-economic solutions for the recovery of Ukraine are:

1) harmonization with the level of global requirements for decision-making regarding the established socio-economic and ecological development of the country and the reconstruction of its regional development;
2) prioritization of the development of the economy of regions and territorial communities, taking into account the ecological factor as a system-forming factor in the concept of sustainable development of the state;
3) audit of effective management and use of natural potentials of regions, on the basis of which it is possible to adopt complex socio-economic decisions regarding sustainable ecological development of regions;

4) implementation of ecological development concepts of the territories of Ukraine to the strategies and development programs of the European community thought the activation of an inclusive consultative process among ecological, economic, demographic, political and economic experts, representatives of the business community, local self-government bodies and other groups of stakeholders who provide geographic, ecological and economic balance of territorial development as well as their careful socio-ecological and economic use.

Thus, the strategic directions of restoration and sustainable development of Ukraine regions proposed in the study, based on ecologically neutral solutions, will make it possible to stop the process of socio-economic and ecological degradation of the regions. The introduction of alternative spheres of economic activity will contribute to the improvement of the life quality for local communities and and support the return of internally displaced persons as well as refugees, who left the country.

Further research will be aimed at forming objective criteria for assessing the level of further established development of socio-economic and ecological regional systems and their level of balance to the requirements of the European Union, taking into account the non-renewability of some natural resources.

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Ukrainian social sector development in contemporary conditions: problems and areas for their solution

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Ukrainian social sector development in contemporary conditions: problems and areas for their solution

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Abstract. The article is devoted to the adaptation of social policy's conceptual framework to war conditions, radical growth of defense spending, which, against the background of production infrastructure destruction and declining business activity, lead to critical underfunding of social sector. The authors emphasize the priority of population's quality of life characteristics as a criterion for assessing functioning of social sector's clusters and a basis for updating social policy's principles and priorities. The study identified the main social sector development problems, which primarily include: limited resources in response to the social sector's growing needs, including social protection; reduced access to medical and educational services; insufficiently effective reforms during the period of war; depopulation; increased migration flows, etc. The following priority areas have been identified for their resolution: creation of conditions for increasing the birth rate, and socialization of senior citizens; effective migration policy; reforming the wage system; simplifying access to professional pre-university and higher education; adapting the network of medical institutions to population's growing needs; preserving and restoring social infrastructure, etc. Development and implementation of measures within the mentioned areas will contribute to social sector development and, accordingly, to the improvement of population's quality of life.

1. Introduction

Russia's full-scale military aggression against Ukraine has brought a lot of grief and hardship to the population [1]. Thousands of servicemen and civilians have been killed, and many businesses, homes, communal and social infrastructure facilities have been destroyed [2]. At the same time, Ukraine's struggle for its independence and freedom has prompted the country to realize its personal civilizational choice, which contributes to democratization of society and progressive economic and social transformations.

Under these circumstances, restoration of social sector, which ensures standard of living and quality of life, is of strategic importance for country's social and economic recovery. Social sector recovery under conditions of war, deep social and economic crisis, global economic and technological challenges require development of a concept that provides for coordination in time and space of fundamental areas of certain actors' actions, use of resources required for this purpose, and determination of expected results.

The purpose of this article is to single out the current problems of social sector development and to substantiate directions for their solution. Achievement of this purpose entails formation of the following tasks: to analyze the level of population's quality of life and to argue for the expediency of using it as an indicator of social sector development; to identify current problems of Ukrainian social sector development and to determine priority areas for their solution.

2. Literature review

Studies devoted to the problems of social sector during war mainly proceed from the thesis that social sector's additional needs for resources are formed depending on the scale of losses in population's quality of life and are used to quantify the number of groups that have suffered damage to health or economic well-being; have been deprived of factor income sources or even ability to work; have been forced to stop studying [3–5]. Less widespread are studies that take into account the depth of gap between the existing quality of life characteristics and social norms and standards as a prerequisite for increasing the burden on social sector, and the extent of available resource support for the social sector shortage as a basis for assessing the need for additional resources to ensure its functioning in line with the urgent needs of society. At the same time, these studies consider the level of efficiency of using the available resource potential, firstly, as a given, and secondly, independent of the institutions' quality (policies and procedures used in the process of its implementation) [6]. Accordingly, our study aims to close this gap by taking into account the importance of institutional changes, updating policies and procedures used in the process of their implementation in order to obtain better social results.

3. Methods

The database for analytical component of the study was compiled from statistical sources of the Ministry of Social Policy, the State Statistics Service, the National Bank of Ukraine, the Pension Fund of Ukraine, Eurostat, as well as from news portals and researchers' publications. In order to accomplish the tasks set, methods of comparative analysis and deduction were used to identify development problems, as well as methods of systematization and generalization – to identify priority areas for solving social sector's problems. For quantitative assessment, the study used methods of time series analysis, analytical grouping to assess dynamics of quality of life's individual components and to highlight contribution of individual social sector's clusters to dynamics of meeting basic population needs. Calculation results became the basis for further use of synthesis method to rank the problems of social sector development in Ukraine and to select priority directions for their solution. Generalization method was used in order to formulate conclusions from the study.

4. Results of the study

4.1. Quality of life as an indicator of social sector development

The multidimensionality of human life generates numerous discussions about approaches to determining the level and quality of life. The most popular integral indicator for assessing quality of life in terms of practical application is human development index, which in general is a combination of three components – level of well-being, life expectancy and education. Diversity of visions on the concept of quality of life has stimulated emergence of numerous methods for assessing its level. In particular, Polozhentseva, when studying income inequality, identifies such components of quality of life as life expectancy, efficiency of health care system, level of income and level of education [7]. Eurostat, when assessing quality of life, identifies the following indicators: material surroundings (income, consumption and material conditions); productive or core activities; health, education, leisure and social interaction, economic security and physical security, governance and fundamental rights, natural and living conditions, and general life experience [8]. In Ukraine, the state recognizes an approach that assesses the standard of living based on the level of wages and pensions, their compliance with social guarantees, consumer price and poverty indices. At the same time, scholars have proposed to enrich these indicators with others, such as those characterizing health, education, transport infrastructure, etc. [9]. Thus, when assessing quality of life according to each of the listed approaches, it is necessary to turn to indicators that characterize the state of social sector through the prism of its services accessibility to the population. Therefore, it can be argued that it is reasonable to use quality of life level as an indicator of social sector development. For instance, the level of pensions, the amount of state social standards and guarantees characterize the state of social protection system development, indicators of public access to healthcare and education services – the state of education and healthcare systems development, etc.

The extraordinary events taking place in Ukraine in recent years (pandemic and introduction of quarantine restrictions, war, increased internal and external migration flows, etc.) have led to a deterioration in the standard of living and quality of life, as evidenced by dynamics of average wages and pensions in dollar terms (figure 1), as well as data on the ratio of average wages and pensions to the actual subsistence level for the respective category (figure 2).

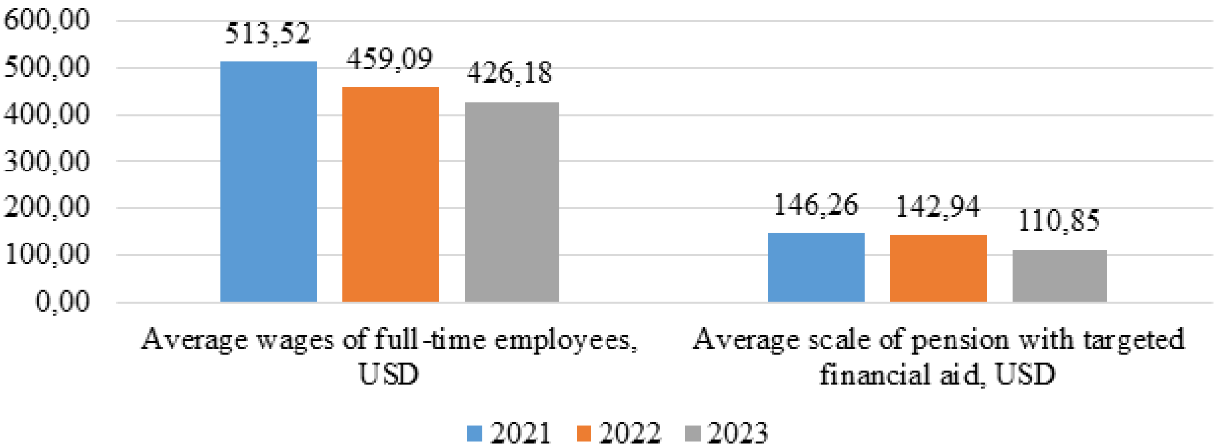

Figure 1. Dynamics of average wages and average scale of pension in 2021-2023, USD (on the basis of [10–13]).

Thus, the average wages of full-time employees during the two years of martial law decreased from \$513.52 in 2021 to \$426.18 in 2023, which means a 17% decrease. The average scale of pension for the same period decreased from \$146.26 to \$110.85, i.e. by 24.2%. The ratio of basic social standards and guarantees is even more revealing. Thus, in 2023, the officially approved subsistence level was only 41.9% of the actual subsistence level, which indicates a significant reduction in all social transfers and wages to budget institution employees. Moreover, this approach practically leads to equalization in labor remuneration: wages from the 1st to the 12th tariff category in the unified tariff net are minimal.

Real wages decreased by 11.4% in 2022. Obviously, the war has significantly deepened pre-existing social problems. According to the World Bank, the level of poverty in Ukraine increased tenfold during the war. All this led to a decrease in population's purchasing power, which directly affected the level of access to educational and medical services.

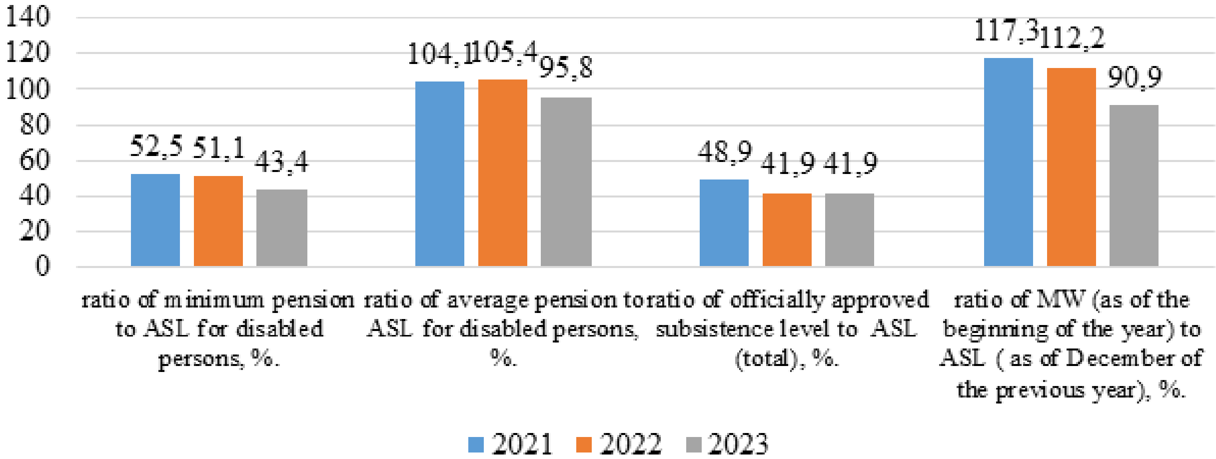

Figure 2. Dynamics of the ratio of certain social standards and guarantees in 2021-2023, USD (on the basis of [14–16]).

At the same time, in nominal terms, there has been a slight increase in incomes (table 1), which in basic indicators is lower than the composite inflation index.

Table 1. Key indicators in the field of household income in Ukraine in 2021-2024 (* for three quarters of 2023, ** composite inflation index for three years) (on the basis of [11–13, 17–19].

Indicators	2021	2022	2023	2024	2024/2021,%
Average wages of full-time employees, UAH	14014	14847	16849,7*	n/a	n/a
Minimum wage as of beginning of the year, UAH	6000	6500	6700	7100	118,33
Average scale of pension with targeted financial aid (as of beginning of the year), UAH	3507,51	3991,53	4622,59	5385,25	153,49
Minimum pension, UAH	1769	1934	2093	2361	133,47
Consumer price index, %	109,4	120,2	112,9	n/a	148,46**

Decline in actual income indicators demonstrates a threatening decline in living standards in Ukraine, which has negative consequences for social sector development.

4.2. Current problems of social sector development in Ukraine

In order to understand current problems in social sector development, it is necessary to note prerequisites for social sector development that formed before the full-scale invasion. These include: high human potential, as evidenced by Ukraine's 77th position in the Human Development Index 2021 and its belonging to the group of countries with a high human development index; an extensive network of social infrastructure facilities (education, culture, healthcare, social security, housing, transport and communications); increased mobility in educational programs; reforming the healthcare sector on the principle "money follows the patient"; increasing housing support programs, etc.

At the same time, social sector development was also affected by unfavorable factors, the negative impact of which deepened with the beginning of Russia's full-scale invasion into Ukraine.

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At the same time, social sector development was also affected by unfavorable factors, the negative impact of which deepened with the beginning of Russia's full-scale invasion into Ukraine. Among them: low GDP per capita ($4,825.4 in 2021, which was only 108.8% compared to 2016; in 2022, this figure deteriorated significantly and amounted to only 77.5%); high level of clandestine employment and "envelope" wages; high level of corruption (in 2021, Ukraine ranked 122nd out of 180 in the Corruption Perceptions Index, scoring only 32 points out of 100); significantly lower life expectancy than in developed countries (69.77 years according to 2021 data, Switzerland – 83.23 years; Canada – 83.80; Japan – 84.83; France – 82.59; Austria – 82.27; Germany 81.51; Poland – 78.76); significant polarization of population by the quality of their life; depopulation; low level of funding for the main components of social sector (in 2021: education – 5.7% of GDP. At the same time, the Law of Ukraine "On Education" stipulates that budget funding should be at least 7% of GDP; healthcare – 3.74%, which is 1.26% less than stipulated by law); dispersion of financial resources and irrational distribution of financial resources (education: there is a practice of placing a state order for 1-2 places, which, in the absence of fee-paying students, leads to unprofitability of the educational program and, accordingly, a decrease in educational services quality), and others.

Social sector functioning has been significantly hampered by military activities. Many social infrastructure facilities have been completely destroyed, and some have been damaged. According to the World Bank [19], the sectors most affected by Russian aggression in Ukraine are housing, transportation, energy, trade and industry. The losses are concentrated in the frontline regions, in particular Donetsk, Kharkiv, Luhansk, Zaporizhzhia, Kherson, Mykolaiv, and in the regions returned to government control, such as Kyiv and Chernihiv regions. Disruptions in economic flows and production, as well as additional war-related costs, are estimated as losses, totaling around USD 290 billion. Ukraine's GDP declined by 29.2 percent in 2022, and poverty increased from 5.5 percent to 24.1 percent in 2022 (based on a poverty threshold of USD 6.85 per person per day).

Educational and healthcare facilities also sustained significant damage. As of November 2023, 365 educational institutions and 193 medical facilities were completely destroyed, and 3428 educational institutions and 1468 medical facilities were damaged [20, 21].

In the context of new challenges emerging during the war, it is worth noting a sharp increase in need for social support for the population while financial resources are limited. In 2022, funding for social protection expenditures increased by 23%, and in 2024, their volume remained almost at the previous year's level. Against the backdrop of high inflation, this increase is offset by a decrease in real funding.

When analyzing social sector's state in times of war, Skipalska [22] notes 4 main problems that are relevant and most significant:

1) *limited resources combined with the growing needs of social sector (due to the increase in the number of IDPs and people in difficult straits).* This problem leads to an increase in the number of challenges social sector has to address. Currently, social services are operating in an under-resourced environment. At the same time, there is a difference in the ability to provide assistance in regions. Additional difficulties arise in occupied and de-occupied territories;
2) *lack of specialists and their experience.* In early 2022, an increase in the number of war refugees led to an outflow of social workers to safer regions or abroad. As a result, many communities are experiencing a shortage of specialists. Unprecedented massive destruction, including houses and civilian infrastructure, has made it impossible in some communities to provide adequate social services at all. Currently, there is an acute need for psychologists. Social workers are only gaining experience in dealing with crisis situations and families who experienced trauma and loss and often require specific assistance or additional forms of training;

3) *further decentralization and reduction of community responsibility.* Currently, communities decide independently how many specialists they need. Under conditions of financial deficit, local authorities neglect the social sector, which leads to the lack of social workers in some communities;
4) *the problem of financing social sector.* Due to large scales, there is an acute problem nowadays, in addition to decentralized centers, of forming a central level structure that would assume funding the most demanded social services at the national level. It is also noted that limited local budgets in wartime complicate this issue.

We cannot fully agree that further decentralization will lead to a slowdown in social sector development. We also do not deem it appropriate to create an additional structure to finance social services.

At the same time, we believe that the following problems in social sector should also be added:

- reduction of healthcare and educational services accessibility due to population's growing needs and insufficiently effective reforms during the war;
- depopulation;
- uneven distribution of labor force by region and with respect to labor market demand;
- destruction of social infrastructure, which will require significant financial and other resources for restoration;
- a significant number of migrants, including children and working-age individuals, most of whom have already adapted in other countries, which will lead to a labor shortage in future should they not return.

All of these and other problems require a more detailed analysis in order to solve them.

4.3. Priority areas for solving social sector problems

Deepening of social sector development problems necessitates revision of areas for their solutions. The main task under current conditions should be overcoming the above-mentioned problems and improving the quality of life of all social groups. The state social policy should be developed in this area, which should become a new policy of social modernization. The social concept of development should focus on the fact that the powerhouse of economic progress is working-age citizens with high labor potential and human capital, significant social activity, mobility, and ability to adapt to the prevailing conditions as quickly as possible and to put their knowledge and skills into practice.

One of the key areas of the abovementioned changes should be creation of conditions for increasing the birth rate and reducing the premature mortality rate. Measures developed in these areas should promote healthy nutrition, careful attitude to one's own health, dissemination of skills for self-preservation behavior during air alerts, etc. In the short term, they will contribute to reducing depopulation rate, and in the long term, to obtaining a positive natural population growth rate, which will contribute to increase in labor force and reduce its shortage in labor market in the postwar period.

In our opinion, the incentive mechanisms to promote appropriate behavioral patterns, both in relation to broad population and companies, are the development of insurance medicine and the introduction of differentiated insurance payment rates. Increasing insurance rates for companies that do not implement measures to reduce morbidity and preserve working capacity (and, accordingly, reducing rates for companies that implement such measures and have evidence of their effectiveness) should become an effective mechanism for stimulating and, at the same time, accumulating financial resources to expand the scope of measures to support families with children.

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5. Discussion

Taking into account the shortage of labor, an effective migration policy should be an important area for solving the abovementioned problems, which will include measures aimed at creating favorable conditions for education, development and employment of young people, especially school graduates, as well as for return of forced migrants and those who left Ukraine before the war in search of better jobs.

An equally important area in this context should be optimal deployment of labor in Ukraine. State support for internally displaced persons should be focused on encouraging them to work and adapt to society in the territorial community where they temporarily reside, and in return to their previous place of residence in the postwar period.

Stimulation and economic (resource) support for moving towards an optimal distribution of labor force should, in our opinion, be based on improving efficiency of labor market functioning, primarily by increasing spatial and professional mobility of the economically active population. Expanding state guarantee programs for education loans and including in the requirements for international partners' investment projects the costs of increasing housing affordability in the regions of project implementation should become an effective means of financial support for increasing spatial and professional mobility of the economically active population.

In view of population ageing, it is worth highlighting creation of favorable conditions for active life of the senior citizens as a separate area of solving the abovementioned problems. In the context of this area, measures should be developed to support this category of people's health, their socialization through involvement in labor and other activities under certain employment and cultural recreation programs, as well as acquisition of new skills (drawing, sewing, design, carving, etc.)

The key areas should also address the issues of accessibility and quality of educational services and medical care. First and foremost, it is necessary to simplify access to professional pre-university and higher education during martial law and in the first 5 years of postwar recovery of Ukraine. Combined with an effective employment policy and provision of a first job, this will help young people make decisions about their future residence and life in Ukraine rather than abroad. In addition, all accreditation procedures should be suspended during martial law, while extending the validity of already obtained accreditation certificates. New programs that have not been accredited before and have been created outside the framework of previously accredited specialties should be accredited under a simplified procedure. All saved funds should be used to create shelters with proper working and resting conditions, as well as to strengthen Ukraine's defense capabilities. Given the significant increase in the number of people with disabilities as a result of Russia's military aggression against Ukraine, the network of health care facilities should be adapted to the current and future needs of the population, taking into account its resettlement. This will contribute to increasing medical care accessibility.

Another key area of change should be creation of conditions that will stimulate economic activity and productivity of all working-age individuals. Wages, including minimum wage, assume an extremely important role in these processes, as they determine the extent of poverty, the boundaries of which are defined by the subsistence level. As was mentioned above, in Ukraine it is unreasonably low. Therefore, poor and low-income people have limited access to basic social services that affect the reproduction of human capital in terms of education, culture, and healthcare; they are forced to save on quality medicine and food. Most of the labor force has low wages. In order to change this situation, the eradication of poverty must adhere to new values and principles of social policy based not only on state support but also on creating conditions for increasing the level of remuneration.

It is important that a significant increase in remuneration, combined with an increase in income elasticity of aggregate supply in Ukraine (which will prevent the effect of nominal wage growth from being eroded by inflation), is also accompanied by an increase in the amount of resources accumulated by social insurance funds and budgets, the revenues of which grow proportionally (and in the case of progressive tax rates, even faster) with the growth of wages

An important area for solving social sector problems is restoration of social infrastructure and housing destroyed as a result of the Russian invasion. It is impossible to solve these problems at the expense of the state budget, so participation of business in these processes is extremely relevant. However, when building a dialogue with business regarding its participation in the implementation of social infrastructure restoration projects, the government should understand that a business entity, even if it implements socially responsible practices and upholds generally accepted human values, will be ready to support social projects only in certain cases, when they do not result in unprofitability of its economic activity and ensures its profitability. And also, if it feels public authorities' not just formal but real support, respect, and appreciation of its efforts aimed at rebuilding important social infrastructure facilities [23].

Ukraine should build a future in which cities and villages that have fallen victim to Russian aggression revive and flourish, forming a social and economic ecosystem where people live in decent conditions and have access to modern technologies that promote sustainable social development and ensure well-being. An important condition for the development of such an ecosystem is its tendency to balance, which is achieved by harmonizing relations in labor and social life of population on region, state and world levels [24].

6. Conclusions

Summarizing the abovementioned, we note the deterioration in quality of life as a result of Russia's armed aggression against Ukraine, which evidences the existence of problems that hinder social sector development. The main social sector problems have been identified: limited resources combined with growing social needs; reduced responsibility of territorial communities regarding social sector development; destruction of social infrastructure, which will require significant financial and other resources for restoration; decrease in accessibility of medical and educational services due to population's growing needs and insufficiently effective reforms during the war; depopulation; increase in migration flows and uneven distribution of labor force by region and with respect to labor market demand.

The following priority areas for their solution have been identified: creation of conditions for increasing the birth rate and reducing the premature mortality rate; effective migration policy that will facilitate return of Ukrainians from abroad, including those who left in search of better jobs before the war; reforming the wage system; simplifying access to professional pre-university and higher education during martial law and within five years after it is lifted; adapting the network of medical institutions to population's growing needs; suspension of accreditation procedures for educational programs during martial law and redirection of the saved funds to the construction and equipment of comfortable shelters for study and recreation in educational institutions; optimal placement of labor in Ukraine and creation of conditions for the continuation of active life of senior citizens. Development and implementation of measures within the mentioned areas will contribute to social sector development and, accordingly, to the improvement of population's quality of life.

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Modeling of the energy security of the country in the context of sustainable development: the case of Ukraine

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Modeling of the energy security of the country in the context of sustainable development: the case of Ukraine

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Abstract. Ukraine's energy industry experienced organizational and territorial challenges, resulting in a coal scarcity and a need for stable and balanced development. Ukraine's unified energy system, which includes a variety of power plants, plays an important role in supplying electricity to other nations. The authors recommend using the multidimensionality principle and a systemic approach to examine the country's energy security, as well as the development of a model based on energy product manufacturing under Ukraine's tough economic and political conditions. Such a theory will show the peculiarities of the production of energy products, which is characterized by a vast collection of qualities and factors that influence it. The factors (or variables) studied in the article are classified as endogenous and exogenous. The E-Views application was used to model the country's energy security in terms of energy product production. The outcomes of the modeling revealed the presence of long-term endogenous and exogenous factors influencing the total volume of energy product production; the existence of a strong relationship between the volume of energy product production and imports, total energy supply, and total final consumption; and opportunities for significant growth in domestic energy product production in the future. The model's practical significance has been demonstrated through reduced reliance on imports, diversification of energy sources, energy independence, energy availability, collaboration in the field of energy security, economic growth, and environmental and sustainable development.The article concentrates the authors' attention on Ukraine's energy sector, which is critical to the country's economy and supply to the EU.

1. Introduction

Faced with global concerns such as climate change, resource depletion, and geopolitical unpredictability, governments throughout the world are being compelled to rethink their energy production capacity, looking for long-term solutions that give both economic prosperity and environmental stewardship. At the intersection of these imperatives is the essential concept of energy security, which encompasses more than just the availability and cost of energy resources, including larger issues of environmental effect, economic sustainability, and social justice. In this paper, the authors investigate the complex relationship between energy security and sustainable development, with a particular emphasis on Ukraine. As a nation at the crossroads of Eastern Europe, Ukraine is dealing with the necessity to ensure a stable and sustainable energy future while matching its trajectory with the principles of sustainable development. Modeling energy security requires a holistic strategy that considers everything from technical progress and the use of renewable energy sources to geopolitical considerations and economic stability. Ukraine, which has a diverse set of energy resources, has traditionally relied on a complex matrix of fossil fuels to supply its energy requirements. However, in recent years, there has been a greater emphasis on diversifying the energy portfolio, improving energy efficiency, and reducing environmental effect. The pressing need to minimize reliance on nonrenewable sources, combined with geopolitical developments affecting traditional energy supply networks, highlights the need and relevance of Ukraine strategically modeling and planning its energy security within the larger context of sustainable development.

2. Literature review

Energy security is defined as the safe and uninterrupted supply of energy resources, which is essential to the operation of the contemporary economy and is linked to national security. The concept of energy security has developed throughout time to include a wide range of concerns. Studies by Abbas and Alqama [1], Popescu [2], and Sutrisno, Nomaler and Alkemade [3] highlight these concerns that include over-reliance on a single source of supply, infrastructure vulnerabilities, and the effects of climate change on energy production. Flaherty and Leal Filho regard them as an economic notion as well as a component of national security, and vulnerabilities in energy infrastructure have both national and international implications [4]. Many countries, as noted by Cherp et al [5], are vulnerable in terms of resource sufficiency, infrastructure reliability, price stability, protection from external threats, and failure resistance. Paleri's study emphasizes energy conservation and sustainable use as crucial aspects of energy security, as excessive energy consumption can harm the ecosystem and deplete resources [6]. Global energy management is critical for addressing energy security concerns and meeting long-term energy demands.

Energy security can be viewed as a component of national security, allowing for an assessment of the vulnerability of the physical infrastructure that transmits energy. Energy security refers to countries' attempts to assure access to a varied range of energy sources, such as oil, natural gas, and renewable energy [4, 7]. Global energy governance is necessary, as is its role in addressing energy security and ensuring long-term energy needs are addressed in a sustainable manner. Misiągiewicz [8], and Paravantis et al. [9] in their research expose the relationship between energy security, economics, and national security, and emphasize the need of a safe and uninterrupted supply of energy resources for the running of modern economies and national security of states.

Energy security in the European Union (EU) is a crucial concern because to its reliance on imports, the Russian invasion of Ukraine, and the post-COVID-19 a pandemic According to Antoniuk and Kulczycka, the EU faced challenges in assuring energy supply from the Persian Gulf region, as well as price instability [10]. The EU's reaction to these difficulties includes a reorientation of energy and security policies, with a focus on eliminating reliance on Russian gas and speeding progress toward the European Green Deal and "Fit for 55" goals [11]. Russia used energy resources as a tool of foreign policy, as emphasized by Yakoviyk and Tsvelikh, resulting in a severe energy crisis in the EU and prompting energy policy adjustments [12]. Streimikiene, Siksnelyte-Butkiene and Lekavičius studied several approaches and instruments to quantify energy supply security and suggested a framework for measuring the dependence and diversification of energy imports in the EU [13]. According to Semenenko et al., the EU responded by implementing steps to strengthen energy security, such as the utilization of renewable energy sources and the diversification of the natural gas market [14].

The authors agree with Vasylyna's study that Ukraine's energy security is a major worry due to its reliance on energy imports, threats of economic and political influence from other nations, and reliance on the global market [15]. The development of vital technologies, such as renewable energy sources, as highlighted by Brych, Putsenteilo and Hunko in their study, is critical for maintaining energy security and enhancing resource efficiency [16]. The war and occupation of

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a portion of Ukraine's land posed an even greater threat to national energy security, resulting in energy sector losses [17]. The fundamental disadvantage of Ukrainian legislation, as examined by Malinovska and Vysochanska, is the lack of a systematic strategy to ensuring energy security [18]. According to Antoniuk and Kulczycka, Ukraine has a strong energy sector that ranks among the top in Europe in terms of installed power generation capacity and gas production [10]. The usage of renewable energy sources is thought to be good for energy security and the long-term development of Ukraine's energy industry.

3. Materials and methods, starting hypotheses

The authors recommend using the multidimensionality principle and a systemic approach to examine the country's energy security, as well as the development of a model based on energy product manufacturing under Ukraine's tough economic and political conditions. Such a theory will allow us to show the peculiarities of energy product manufacture, which is characterized by a wide range of features and influencing variables. Such factors (or variables) can be classified as either endogenous or exogenous.

The effective use of endogenous elements enables Ukraine to construct a balanced and sustainable energy system, stimulate future economic development, and reduce reliance on imported energy sources. For example, developing renewable energy sources and improving energy efficiency are critical to the energy sector's long-term development. Endogenous elements in Ukraine's energy product production include internal resources and potentials that can be exploited to generate electricity and other energy products. The key endogenous elements in this context include a wide range of energy sources and technologies, including coal, natural gas, nuclear power, renewable energy sources, hydropower, energy efficiency, and the usage of modern technologies. Exogenous factors are vital and necessary for developing a sustainable energy policy in Ukraine, as well as promoting energy security and the country's long-term growth. Exogenous factors affecting Ukrainian energy product production include external influences and events that may have an impact on the country's energy sector. These elements include the geopolitical context (wars), international commitments, technological innovations, raw material costs, and energy demand and consumption.

To model the country's energy security based on energy product production, we will use the E-Views application. The multivariate regression model appears like this:

$$Y = f(X_1, \ldots, X_n) \tag{1}$$

We will investigate the influence of external and endogenous elements, as well as the density of their connections, using the model that has been developed. The use of E-Views comes from the fact that it is one of the most powerful packages for developing econometric models, allowing researchers to simulate an economic process, examine a hypothesis, and generate a forecast.

Based on the statistics data from World Energy Balances Highlights 2023 [19], our model will comprise 12 observations from 2010 to 2021. When selecting the most significant factors, we apply the reliability principle, which adequately reflects the current state of energy product production in Ukraine, the information availability principle, which requires the use of official data, and the representativeness principle, which states that each variable chosen for the sample is the most significant and justified.

The author's hypothesis is that the general production of energy products in Ukraine at the current stage is affected by the political and economic situation, namely the war.

The general appearance of the country's energy security model based on the production of energy products is described by the following linear equation:

$$P = f(I, S, TC), \tag{2}$$

where, P – production of all energy products (coal, peat, oil shale, oil products, natural gas, nuclear, renewables and waste, electricity, heat), I – import of energy resources, S – total energy supply, TC – total final consumption.

4. Results

4.1. Creating a model in line with the hypothesis

We used a variety of parameters in the $f(P)$ research procedure, including energy resource imports and exports, electricity, total final energy consumption, industry, transportation, and power production. The three most important elements influencing the creation of all energy products in Ukraine are energy resource imports (I), total energy supply (S), and total final consumption (TC). So, in the process of analysis according to the Prob. criterion, which reveals the most significant effect on *f*, we produced the following equation:

$$P = C(1) \times I + C(2) \times S + C(3) \times TC + C(4) \tag{3}$$

The module is built on the basis of the data given in table 1.

Table 1. Database for model.

Year	Production (PJ*)	Imports (PJ)	Total energy supply (PJ)	Total final consumption (PJ)
2010	3301	2146	5541	3096
2011	3587	2431	5299	3170
2012	3576	1947	5129	3036
2013	3615	1666	4863	2934
2014	3239	1440	4424	2570
2015	2701	1317	3887	2127
2016	2662	1218	3835	2167
2017	2464	1469	3743	2088
2018	2549	1415	3916	2152
2019	2531	1453	3741	2079
2020	2387	1283	3616	2000
2021	2290	1346	3692	2051

Based on the selected most significant factors, a correlation matrix was constructed that shows the close relationship between the selected factors (table 2).

Table 2. Correlation matrix of selected variables.

	P	I	S	TC
P	1	0.77008	0.91946	0.95773
I	0.77008	1	0.90691	0.89578
S	0.91946	0.90691	1	0.98879
TC	0.95773	0.89578	0.98879	1

The relationship between the selected factors is positive and strong: between P and TC is 95.8%, between P and S – 91.9%, between P and I – 77%.

The results of further regression analysis are given in table 3, which makes it possible to assess the impact of selected variables on the production of all energy products in Ukraine using data for the twelve-year period 2010-2021.

The results of the regression analysis under the conditions of establishing a marginal 5-10% level of significance are:

Table 3. Results of multi-factor regression of P (least squares method, sample 2010–2021, 12 observations).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
I	-0.467249	0.186403	-2.506656	0.0366
S	-0.653663	0.298190	-2.192104	0.0597
TC	2.361913	0.427114	5.529939	0.0006
C	668.3830	259.0415	2.580216	0.0326
R-squared	0.972702	Mean dependent var		2908.500
Adjusted R-squared	0.962465	S.D. dependent var		513.1008
S.E. of regression	99.40758	Akaike info criterion		12.29754
Sum squared resid	79054.93	Schwarz criterion		12.45917
Log likelihood	-69.78521	Hannan-Quinn criter.		12.23769
F-statistic	95.02058	Durbin-Watson stat		1.418393
Prob(F-statistic)	0.000001			

- the analysis of the coefficients of the equation showed that the value of P directly depends on the variables we have chosen;
- the R^2 regression result in this table is 97.3%, indicating how closely the variables in this model we choose are related to the production of all energy products. The regression result indicated that P has a sufficiently strong relationship with the elements we chose to influence it. In addition, the corrected $R_[adj]^2$ is high, at 96.2%. The chance of adopting H_0 is close to zero (F-statistic=0.00), supporting the hypothesis about the equation's overall importance. The relevance of the selected variables in terms of impact on P is confirmed as follows: GFSI: 3.6% energy resource imports; 5.9% total energy supply (within the 10% significance threshold); and 0.6% total final consumption. We chose variables that perfectly conform to the defined level of significance, which is fewer than 5-10%. In general, there are no strict criteria for the constant, although in our instance it is also statistically significant;
- analysis of the DW criterion helps to test our equation for autocorrelation. The value of the DW criterion lies in the range from 0 to 4; in our case, this criterion (DW) is 1.41. Statistics DW helps to determine critical points d_l and d_u. At the level of significance α=1%, we have 0.449<DW<1.373; our value is greater than d_u=1.373, which means there is no autocorrelation of the residuals and we have no reason to reject H_0, that is, we take it as a basis;
- the analysis of information criteria used in building this model showed that Akaike (AIC) and Schwarz (BIC) are 12.3 and 12.5, respectively, which are small acceptable values for the model.

4.2. Testing the autocorrelation model, the presence of heteroscedasticity and the quality of the selected factors in the model

Verifying the model for first-order autocorrelation revealed its absence; we next tested the model for the presence of higher (second) order autocorrelation using the Breusch-Godfrey test (table 4); verifying autocorrelation is reduced to testing the null hypothesis.

Table 4 has strong indications of Prob values. F(2,6) at 45.6% and Prob. Chi-Square(2) at 25.1%, which is greater than the 10% significance level. When using the following lag 3 values of Prob. F(3,5)= 69.2%, and Prob. Chi-Square(3)=42.1%; when using lag 4, the value of indicators is also more than 10%. This allows us to accept H_0 and is evidence that there is no higher (second) order autocorrelation.

Table 4. Breusch-Godfrey serial correlation LM (presample missing value lagged residuals set to zero).

F-statistic	0.897863	Prob. F(2,6)	0.4559
Obs*R-squared	2.764169	Prob. Chi-Square(2)	0.2511
R-squared	0.230347	Mean dependent var	-2.65E-13
Adjusted R-squared	-0.411030	S.D. dependent var	84.77507
S.E. of regression	100.7016	Akaike info criterion	12.36905
Sum squared resid	60844.83	Schwarz criterion	12.61151
Log likelihood	-68.21432	Hannan-Quinn criter.	12.27929
F-statistic	0.359145	Durbin-Watson stat	1.463408
Prob(F-statistic)	0.859537		

The next step is to test this model for heteroskedasticity based on the Breusch-Pagan-Godfrey, Glejser, ARCH, White, Harvey tests (table 5).

Table 5. Results of heteroskedasticity test (least squares method).

Breusch-Pagan-Godfrey test, dependent variable – $\text{RESID}\hat{2}$			
F-statistic	0.575653	Prob. F(3,8)	0.6470
Obs*R-squared	2.130523	Prob. Chi-Square(3)	0.5458
Scaled explained SS	1.228681	Prob. Chi-Square(3)	0.7461
Glejser test, dependent variable – ARESID			
F-statistic	0.690370	Prob. F(3,8)	0.5830
Obs*R-squared	2.467784	Prob. Chi-Square(3)	0.4811
Scaled explained SS	2.104368	Prob. Chi-Square(3)	0.5510
ARCH test, dependent variable – $\text{RESID}\hat{2}$			
F-statistic	0.046743	Prob. F(1,9)	0.8337
Obs*R-squared	0.056835	Prob. Chi-Square(1)	0.8116
White test, dependent variable – $\text{RESID}\hat{2}$			
F-statistic	0.305520	Prob. F(9,2)	0.9145
Obs*R-squared	6.947027	Prob. Chi-Square(9)	0.6426
Scaled explained SS	4.006376	Prob. Chi-Square(9)	0.9110
Harvey test, dependent variable – LRESID2			
F-statistic	0.517768	Prob. F(3,8)	0.6817
Obs*R-squared	1.951120	Prob. Chi-Square(3)	0.5826
Scaled explained SS	3.583219	Prob. Chi-Square(3)	0.3101

The analysis of table 5 proved the probability of accepting H_0 and the absence of heteroscedasticity:

- according to Breusch-Pagan-Godfrey test, Prob. F(3,8)=0.6470 and Prob. Chi-Square(3)=0.5458;
- according to ARCH Prob. F(1,9)= 0.8337 test, Prob. and Chi-Square(1)=0.8116;
- according to White Prob. F(9,2)= 0.9145 test, Prob. and Chi-Square(9)=0.6426;
- according to Harvey test, Prob. F(3,8)= 0.96817 and Prob. Chi-Square(3)=0.5826;
- all tests for heteroscedasticity showed its absence and the probability of accepting H_0>5-10%.

The next step is to check the model for the quality of the selected influencing factors on the production of all energy products based on the Ramsey and Chow tests (table 5 and table 6).

Table 6. Results of Ramsey RESET test (squares of fitted values are omitted).

	Value	df	Probability
t-statistic	0.420552	7	0.6867
F-statistic	0.176864	(1, 7)	0.6867
Likelihood ratio	0.299428	1	0.5842

Table 7. Results of Chow forecast test for observations from 2015 to 2021.

	Value	df	Probability
F-statistic	29.19535	(7, 1)	0.1416
Likelihood ratio	63.89761	7	0.0000

The Ramsey RESET test-based approach for assessing the functional form determines whether any components were mistakenly omitted from the model that have a major impact on the production of all energy products in Ukraine. The F-statistic is 17.7% at df(1.7), which above the 5% significance level. This indicates that the regression is statistically significant, and the linear form of the model we chose is correct.

The Chow forecast test ensures that the regression model's parameters remain stable. The F-statistic is 14.2% at df(7.1), which above the 5% significance level. This means that we accept H_0 in the model, that there are no structural fractures in the sample, and that the model is solid in structure.

4.3. Testing the model for normality of residuals, explanatory power, and predictive quality

The residual normality test (figure 1) is the next stage in ensuring the generated model's accuracy.

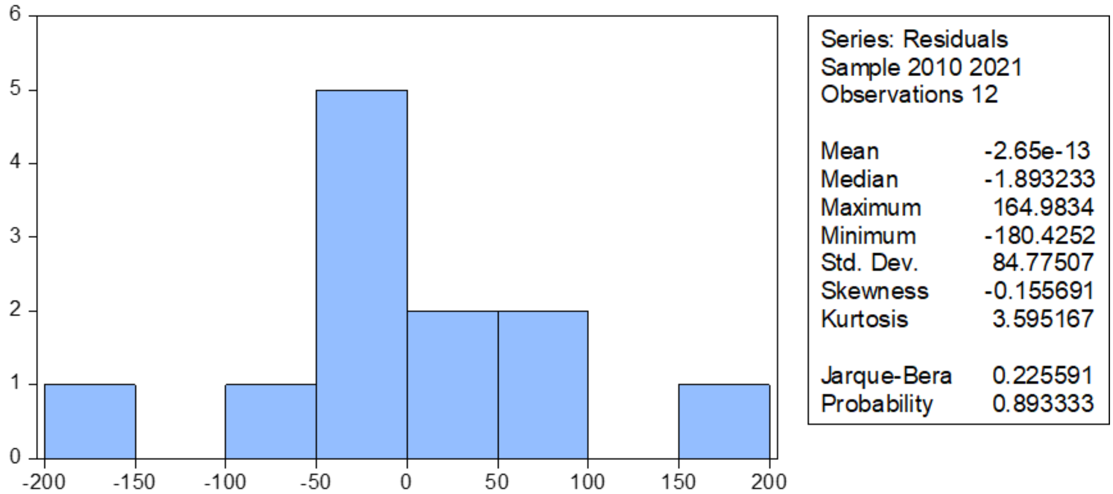

Figure 1. Normality test in $f(P)$.

Figure 1 demonstrated that the model's residual distribution is normal. Kurtosis =3.6, which is larger than zero and implies a steeply peaked distribution; a low value indicates that the distribution is near normal. The average level of production of all energy products was found to be intriguing, with a value of -1.89, indicating the impact of substantial negative factors on the overall volume of production of energy products in Ukraine, which is related to the conduct of the conflict. At the same moment, the probability of accepting H_0 is 89% (high).

The next step in evaluating the developed model is to assess its explanatory power, or how well the selected components arising from changes in the researched variables represent the Ukrainian model of energy product production (figure 2).

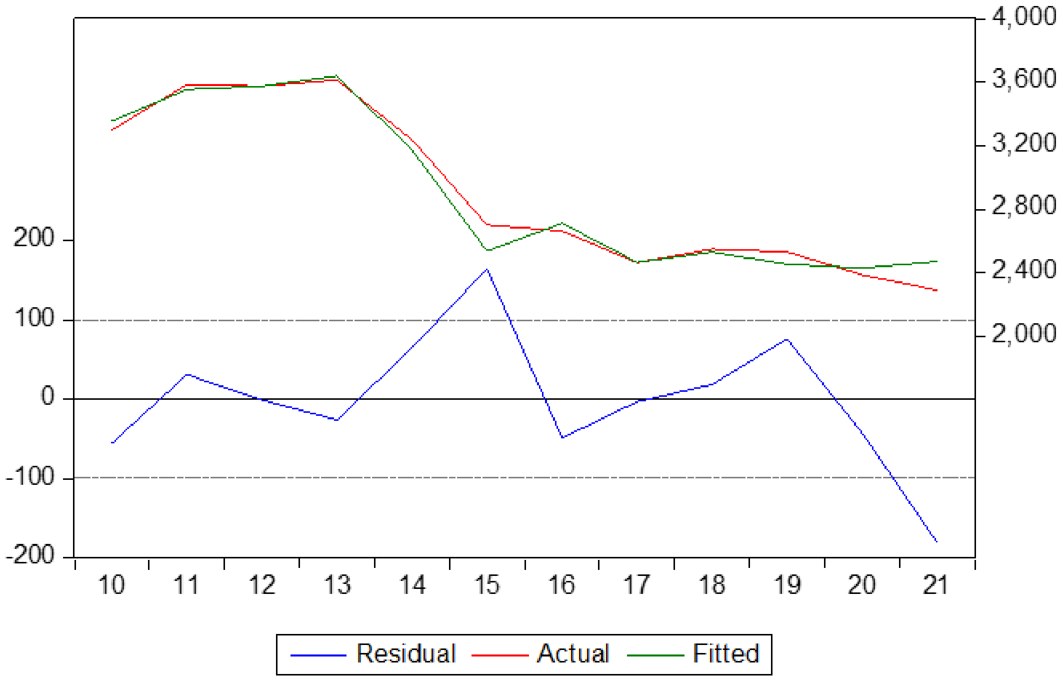

Figure 2. Explanatory ability of the model.

As figure 2 illustrates, the simulated values closely match the actual, true values. This demonstrates that the model we created fits all of the required criteria and is perfectly acceptable. Figure 3 shows the model's predictive quality.

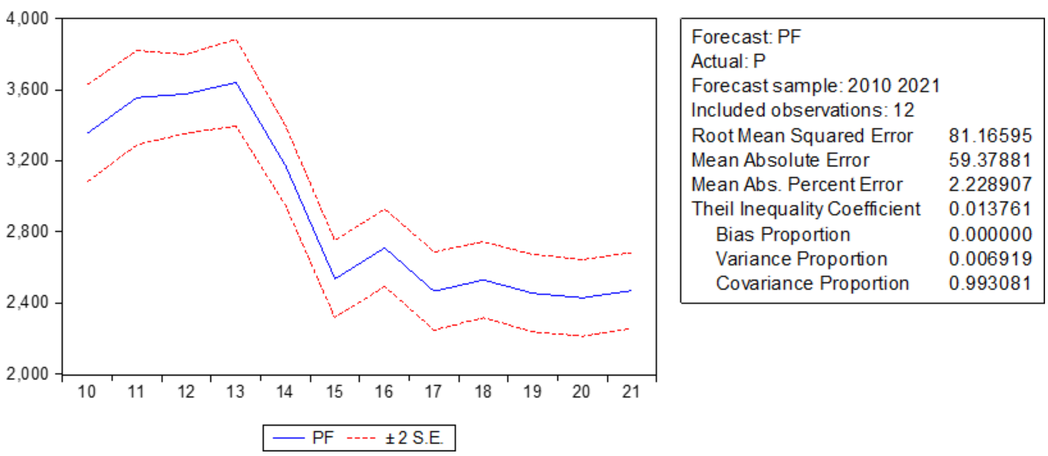

Figure 3. Forecast GFSI.

The forecast, based on data from 2010-2021, as shown in figure 3, implies a reduction in all energy product production in Ukraine after 2014, which is linked to the annexation and occupation of certain of Ukraine's territory. The environment became more stable between 2019 and 2021, and Russia's full-scale invasion of Ukraine had unfavorable implications. The MARE indicator is 2.2%, indicating that the forecast is both accurate and high-quality.

The authors' model completed all relevant tests, including autocorrelation, heteroscedasticity, factor quality, residual normality, explanatory power, and predictive quality. All tests and checks ensure that this model is correct for Ukraine. This means that:

- the equation is statistically significant with a high coefficient of determination;
- the equation represents an economic-mathematical model at a high level of quality;
- the model built by the authors is adequate and fully acceptable for forecasting in the future.

The model's general look is given by the following linear equation:

$$P = -0.4672 \times I - 0.6536 \times S + 2.3619 \times TC + 668.3830 \tag{4}$$

Therefore, the model proposed by the authors based on the selected most significant factors, namely import, total energy supply and final consumption, is developed with an emphasis on domestic energy production. This model of Ukraine's energy security has practical value in the following areas:

- the energy security model is aimed at reducing dependence on imports. By prioritizing domestic energy production, Ukraine is reducing its dependence on external sources. Given the current state of full-scale war in Ukraine, as well as historical tensions and geopolitical difficulties, reducing dependence on external energy suppliers strengthens Ukraine's sovereignty and will help reduce vulnerability to external pressure or manipulation in the future;
- the diversity of energy sources. In order to ensure energy security, Ukraine must prioritize domestic energy production. This allows the state to diversify its energy balance, minimizing vulnerability to supply disruptions or price variations for any given energy source. This diversification may include renewable energy sources such as natural gas, coal, and nuclear power;
- the energy independence, which ensures the energy security of Ukraine. Building a reliable and efficient domestic energy production infrastructure strengthens Ukraine's energy independence. This independence not only strengthens national security, but also provides stability for economic growth and development by ensuring a consistent and reliable supply of energy to industry, business and households;
- the economic growth. Investment in domestic energy generation generates jobs and encourages economic growth in Ukraine, both presently and in the future. This is especially real and noticeable when the expansion of the energy sector is paired with investments in research, innovation, and technology, which contribute to the construction of a trained workforce and the development of local industry;
- the environmental and sustainable development. A paradigm that promotes local production has the potential to provide environmental benefits, depending on the primary energy sources used. Investments in renewable energy sources, for example, can help to reduce greenhouse gas emissions, improve air quality, and support global efforts to battle climate change and achieve the Sustainable Development Goals. Thus, according to Ukraine's environmental strategy, by 2030, 17% of energy will be obtained from renewable sources (now, this figure does not exceed 6%), and the energy intensity of the economy would be halved [20];

- the energy availability. A full-scale war in Ukraine changes the attractiveness of investments, particularly in the energy industry. At the same time, it is worth noting that the initial investment in domestic energy production infrastructure can be substantial, resulting in more stable energy prices in the long run. By reducing its reliance on imported energy sources, Ukraine can limit the impact of external factors on energy costs, providing more stability and affordability for customers;
- the collaboration on energy security, particularly with European countries. A dependable local energy production strategy can promote energy security collaboration with neighbouring countries and international partners. Ukraine can create diplomatic relations and promote regional stability by reaching agreements on energy supply, infrastructure development, and emergency response measures.

The model developed by the authors proposes not only a way to meet energy needs, but also to promote economic development, environmental sustainability and international cooperation.

5. Discussion

When revealing this issue, it is important to acknowledge its intricacy and multifaceted nature. In the process of focusing on Ukraine's energy security in the context of sustainable development, the optimal mix of energy sources to ensure energy security and sustainable development in Ukraine, as well as how to balance the use of renewable and traditional energy sources to ensure sustainable development, are contentious issues that require further investigation. Because many countries rely on imported energy, it is critical to identify future ways to reduce dependence and secure domestic energy security, as well as establish plans for developing local energy sources that can help reduce reliance on other countries.

Technological advances also play an important role in energy security, and can be leveraged to improve energy security and development in Ukraine. Furthermore, its execution will have an impact on both economic development and the environment, in addition to ensuring appropriate energy security.

Further research in this area might include an assessment of the influence of sustainable development goals on total energy production, as well as prospects for Ukraine's EU membership in terms of energy security.

6. Conclusions

The analysis of the country's energy security, taking into account the war in Ukraine and the formulation of a model based on the production of energy goods, revealed:

- the long-term presence of factors of endogenous and exogenous origin that affect the total volume of production of energy products, which is a necessary and sufficient condition for ensuring energy security, the formation of a balanced and sustainable energy system in Ukraine under conditions of sustainable development;
- the existence of a strong connection between the volume of production of energy products and the researched and analyzed factors – import of energy resources, total energy supply, total final consumption, correlation coefficients are 77%, 92% and 96%, respectively;
- a 1% increase in general energy product imports results in a 0.5% drop in total domestic energy product production. With a 1% rise in overall energy supply (Total energy supply = Primary production + Recovered and Recycled products + Imports – Export + Stock changes – International maritime bunkers – International aviation), the total volume of output of domestic energy products decreases by 0.65%. A 1% increase in total final energy consumption (which includes energy consumed by industry, agriculture, and homes) results in a considerable rise in domestic energy product production.

- this model's practical value is exposed, since it is primarily focused at domestic energy generation, which will boost energy security while also contributing to economic development and environmental sustainability. The model's practical value is accomplished through reduced dependency on imports, diversification of energy sources, energy independence, energy availability, and collaboration in energy security, particularly with European countries.

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Interconnected roles of human capital, employment, and sustainable development in the EU countries

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Abstract. Ensuring social stability and environmental sustainability is crucial for implementing the Sustainable Development Goals in European Union (EU) countries. This paper aims to explore the interdependencies among human capital, employment, and resource productivity in these countries, focusing on sustainable development. To comprehensively assess factors influencing sustainable development in the EU countries, the simultaneous model is proposed. The simultaneous equations were derived using a two-step least squares method. The model comprises three endogenous variables (human capital, quantified by students enrolled in tertiary education; employment, in terms of the resident population concept; and resource productivity) and ten exogenous variables. The human capital pillar for the EU countries hinges on public funding for tertiary education, the employment dynamics for tertiary-educated individuals, resource productivity, environmental taxation, and emigration. Employment requires monitoring demographic trends, resource productivity, government funding for tertiary education, and environmental taxation. The environmental pillar depends on employment dynamics, GDP per capita, public funding for environmental protection, material resource extraction, and direct material inputs of fossil energy materials. For Austria, Belgium, and Portugal, from 2013 to 2021, the theoretical values based on the structural model of sustainable development demonstrated good forecast accuracy for human capital, employment, and resource productivity, indicating positive dynamics.

1. Introduction

The integration and cooperation of Ukraine with European Union (EU) countries present a pivotal strategic foundation for the modernization of the national economy, both preceding and amid the full-scale Russian invasion into Ukraine. Furthermore, the collaboration establishes the crucial conditions for attaining the Sustainable Development Goals (SDGs), elevating the standard of human capital, bolstering overall employment rates, and protecting the environment. Given the post-war reconstruction initiatives in Ukraine, elucidating the nuanced dependencies between human capital, employment dynamics, and sustainable development in the EU countries assumes heightened significance.

Within the framework of the global initiative set forth by the United Nations (UN) to effectuate a comprehensive transformation of the world by the year 2030, [1], the EU countries are actively forging national and international partnerships to fulfil the obligations delineated by the SDGs. This implies that each country in the EU has initially customised the set of SDGs to align with the distinctive features of national economic development, social conditions, and environmental status. Consequently, in Poland, the focus on the 4th SDG, "Quality Education", is directed towards fostering an environment conducive to educational development across the entirety of the nation and promoting equal opportunities in education [2, p. 79]. In Germany, the pursuit of this goal is aimed at the ongoing enhancement of both education and vocational training [3, p. 168–169]. In Lithuania, a crucial aspect concerning the "Quality Education" goal involves the acquisition of fundamental and advanced skills at all stages of learning and development. This encompasses the broader and equitable availability of o quality education across various levels, including access to vocational education and training [4]. In other words, at the EU level, the improvement of human capital is ensured by the provision of inclusive and equitable quality education, coupled with the development of opportunities for lifelong learning.

For each EU country, Goal 8, "Decent Work and Economic Growth", encompasses specific objectives and target indicators tailored to the prevailing socio-economic situation and anticipated future changes. For instance, in Poland, a pivotal focus lies in the development of stable employment structures, along with endeavours to augment the labour force participation of young individuals, those aged over 50, long-term unemployed individuals, and those with disabilities [2, p. 95]. In light of this, the EU countries, through the facilitation of employment opportunities, contribute to the heightened efficiency in utilizing human capital and other economic resources. Consequently, this engenders social stability, elevates living standards, and establishes a conductive framework for a productive economic landscape.

At the same time, the EU countries are instituting measures aimed at enhancing the efficiency of natural resource consumption and guaranteeing environmental sustainability. In Germany, the assessment of efficient and economic natural resource employment relies on key indicators such as the productivity of raw material use [3, p. 227–228]. These initiatives are comprehensive in scope and are intricately associated with various SDGs, including Goal 7, "Affordable and Clean Energy", Goal 9, "Industry, Innovation and Infrastructure", and Goal 11, "Sustainable Cities and Communities".

Concurrently, sustainability stands among the foremost priorities of the EU's domestic and foreign policy agendas. EU institutions play a pivotal role in establishing a national framework for the realization of the SDGs and systematically monitor the progress towards achieving these goals [5]. From this perspective, elucidating the complex dependencies between human capital, employment dynamics, and resource productivity in the EU countries becomes imperative for assessing the success of the SDGs and policy decision-making. The utilization of quantitative methods is envisaged to facilitate a nuanced comprehension of the dependencies between these drivers, offering valuable insights for policy aimed at SDG achievement. This approach also holds promise for a deeper understanding of future dimensions related to Ukraine's European integration and post-war recovery.

2. A literature review

Since the publication of Brundtland Report (On our Common Future) [6], discussions on sustainable development of national economies have become a focal point among scholars. Employing non-radical Data Envelopment Analysis (DEA) models, Cyrek and Fura [7] have demonstrated that structural shifts in employment across agriculture, industry, market, and non-market services in highly developed EU countries contribute favourably to the achievement of SDGs. Through the application of panel data regression models with fixed and random effects, as well as the systemic generalized method of moments, scholars [8] have revealed that the total expenditures on R&D, along with the employment rate of recent graduates, play integral roles in fostering sustainable development in the EU countries. Employing qualitative data analysis, methods of comparison and grouping, and the TOPSIS method, Lapinskaitė and Vidžiūnaitė [9] have ranked the G20 countries based on the indicators of SDG 8 "Decent work and economic growth" to assess the peculiarities of economic growth and the creation of a decent working environment in these G20 countries from 2013 to 2018. Given these insights, employment is recognized as a crucial factor that substantially contributes to the attainment of the SDGs.

Certainly, education stands as an equally vital component of sustainable development. Having analyzed the current and future landscape of education, employment and sustainable development in the EU, Gaballah, Dufourg, and Tondeur [10] have substantiated the pivotal role of "lifelong learning" driven by the rapid evolution of technology. Applying the Butterworth filter and correlation analysis, scholars [11] have elucidated the influence of migration on the attainment of the SDGs in Ukraine. Furthermore, they have identified policy measures aimed at ensuring adequate access to education, creating employment opportunities, and fostering intellectual migration to the country. Building on various theoretical approaches, McGrath, Alla-Mensah, and Langthaler [12] have delineated the connection between skills, vocational education, and training in relation to poverty reduction, economic growth, and decent work within the new paradigm of human and sustainable development.

Applying clustering, cross-effectiveness, and contingency assessment, Puertas and Marti [13] have uncovered inequalities in the sustainable development of municipalities in Spain and Italy, with the exception of the dimensions of People (SDGs 1, 2, 3, 4, and 5) and Prosperity (SDGs 7, 8, 9, 10, and 11). Employing a Logit-Probit modelling, Kuzior et al. [14] have demonstrated a positive and statistically significant impact of financial literacy, duration of compulsory education, government spending on education, student-teacher ratio, and secondary school enrolment on sustainable development. Employing vector autoregressive (VAR) methods and Johansen's VEC approach, Marynych [15] has determined that capital related to labour and education has a positive impact on regional sustainable development in Ukraine. Conversely, the lack of macroeconomic stability and unrealized potential of technological progress have a negative impact. Consequently, based on these findings, education in sustainable development and the pursuit of the SDGs serve as catalysts for positive changes in the national economy.

Moreover, various dimensions exist regarding the impact of education on sustainable development. In an empirical assessment of 179 countries aimed at identifying relationships among key SDGs, Sarwar et al. [16] have demonstrated that over the long term, the coefficients of labour and capital exhibit significance and positivity concerning education and carbon emissions. This suggests that reforms associated with the education system and climate change mitigation policies require an extended period to manifest an impact on the economy. Employing multiple regression and correlation analysis, Kichurchak [17] has revealed that within the framework of sustainable development, budget financing of tertiary education in the EU countries was affected by various exogenous factors. These factors include GDP, total annual net earnings of individuals without children, the labour market situation for individuals with tertiary education, and the number of students enrolled in public tertiary education institutions at the bachelor's or equivalent level. Employing a multifactorial analysis to assess the state of implementation of SDGs for quality education across 28 EU countries, Szymańska and Zalewska [18] have underscored that globalization and the establishment of a unified policy framework within the EU necessitate supplementary endeavours at the domestic level. Through modelling the distribution of years of schooling across the country and employing this model to scrutinize educational inequality since 1970, as well as projecting progress towards the 2030 education-related Sustainable Development Goal (SDG) targets, Friedman et al. [19] have identified significant issues with secondary and tertiary completion rates. Hence, it is imperative to persist in prioritizing the improvement of the education sector to elevate human capital and promote the sustainable development of nations.

Alongside this, rationalizing the use of natural resources is also crucial for sustainable development. By employing multiple regression analysis, Taušová, Tauš, and Domaracká [20] have developed a model enabling the assessment of the capability to achieve the goals established by sustainable development and environmental policy within the EU. This model delineates the significance of the impact of the observed variables on the resultant resource productivity of both the EU member states and the Visegrad countries. Meanwhile, Giljum et al. [21] have determined that the EU's sustainable development policy instruments, focusing on enhancing eco-efficiency at the micro level, can contribute to economic growth. This contribution, however, is accompanied by a slight reduction in domestic production across all European countries and a significant increase in resource productivity.

To enhance the measures of Ukraine's sustainable development strategy, Zomchak [22] has proposed a structural (simultaneous) model incorporating GDP, household income and environmental expenditures as endogenous variables, along with seven exogenous variables. Positioning sustainable development as a conceptual framework for the post-war economy of Ukraine, Martynovych, Yemchenko and Kulinich [23] have outlined a procedure for assessing the effectiveness of Ukraine's socio-economic development after the war. They have accomplished this by defining an integral indicator based on the generalized Harrington's desirability function. Employing panel autoregressive distributed lag (ARDL) to examine the correlation between variables, Sadiq et al. [24] have uncovered a positive impact of environmental, social and corporate governance (ESG), and economic growth on the SDGs in ASEAN countries. To assess the progress in achieving the SDGs in the EU countries and understand the interconnections between them, Kuc-Czarnecka, Markowicz and Sompolska-Rzechuła [25] have employed sensitivity analysis, linear ordering of countries, and Spearman's rank correlation coefficient. Their findings indicate there are more potent synergies among the SDGs than trade-offs. Accordingly, the considerations of environmental protection and economic growth in the context of sustainable development for national economies are gaining relevance in policy-making.

Meanwhile, the processes of fostering a diverse and harmonious society have laid the groundwork for evaluating the role of culture in sustainable development and the implementation of the SDGs. By employing the fuzzy set method of qualitative comparative analysis (fsQCA), incorporating the Hofstede approach to cultural dimensions, and utilizing the SDGs index across 82 countries, Sedita, Blasi and Yang [26] have shown that culture significantly influences the strategies employed by countries in attaining sustainable development. Applying the principal components method and econometric modelling, the dependencies of local budget expenditures on culture in Ukraine on the demographic situation, business activity, and well-being of the population were specified to achieve the SDGs [27]. Based on a logistic regression model, Verina et al. [28] have established a connection between employment in the cultural sector, government spending on culture, the number of cultural enterprises, and sustainable development in the EU countries. Applying panel regression methods with random effects and OLS regression based on the first differences of the relevant variables, Sokół, Pangsy-Kania and Biegańska [29] have shown the influence of cultural industries on sustainable development in the EU countries. Additionally, these contributions have demonstrated that the achievement of the SDGs should be guided by the incorporation of cultural considerations and values, aiming to address complex socio-ecological and economic challenges.

Another strand of research focuses on the role of digitalization, information and communication technologies (ICTs) in the attainment of the SDGs. Sorin-Iulian et al. [30] have developed two-panel data regression models to evaluate the influence of crucial ICT indicators at the EU level on SDGs, including economic growth and the reduction of inequality. Their findings indicate that advancements in the implementation of the digital society have the potential to mitigate income inequality. Focusing on a sample of 140 countries over the period 2000-2019, Nchofoung and Asongu [31] have identified the favourable impact of ICTs on sustainable development through fixed effects estimation, Driscoll and Kraay estimation, middle group estimation, system GMM and Tobit fixed effects instrument variable. To elucidate the initiatives of the sectoral national and regional sustainable development policy, Kichurchak [32] has developed a simultaneous model for the information and communication sector by region of Ukraine. In this model, the equations describe the added value of the production costs of business entities, the number of operating business entities and employees, and the structure of service exports in this sector. In the light of sustainable development and the mitigation of the consequences of COVID-19, Polishchuk et al. [33] have examined the factors of digitalization in the national economies of specific countries and categorized the types of trajectories associated with sustainable economic growth. In essence, the sustainable development of national economies, along with the corresponding policy initiatives, necessitates the consideration of factors related to technological change and the advancement of specific sectors and industries.

Overall, scholars have made valuable contributions in elucidating the complex social, economic, and environmental dimensions of sustainable development. They have involved quantitative methodologies for assessing the impact of employment dynamics and education, ecological and rational resources consumption, culture and ICTs on the SDGs in Ukraine, the EU and other countries. However, this paper proposes to employ structural modelling methods to uncover dependencies and assess the relations that delineate the social and environmental dimensions of sustainable development in EU countries.

The purpose of this paper is to explore the dependencies among human capital, employment dynamics, and resource productivity in the EU countries within the framework of sustainable development, employing econometric methods.

The underlying hypotheses are as follows. Firstly, human capital is posited to be linked to the number of students enrolled in tertiary education in the EU countries, potentially influenced by their expectations of employment, the fiscal capacity of the public budget for funding tertiary education, and current approaches to taxation. Secondly, the number of employees may be interconnected with the prevailing demographic situation in the EU countries, resource productivity, budgetary allocations for education, and taxation. Thirdly, it is suggested that resource productivity may be contingent on the state of employment and public expenditures dedicated to environmental protection in the EU countries. This approach seeks to provide a reasonable explanation for the structure of relationships among these parameters and uncover the factors contributing to sustainable development in EU countries.

3. Research methods

The exploration of the dependencies between human capital, employment dynamics, and resource productivity for sustainable development in the EU countries requires careful consideration of their mutual influences on each other. Methodologically, the most suitable approach for this purpose is a framework of simultaneous regression equations involving two or more dependent variables. In a nutshell, the simultaneous model stands out as an approach enabling the identification of complex dependencies within the ecological and social components of countries.

Accordingly, the variables explicable through the structural equation model, and whose values are determined through the simultaneous interplay of the model variables, can be categorized as either endogenous or jointly determined. Moreover, a comprehensive description of the dependencies between human capital, employment dynamics, and resource productivity in the EU countries requires the careful selection of explanatory (exogenous) variables for the simultaneous model. Indeed, the determination of exogenous or endogenous status for variables in the data sample is contingent upon the expertise of the individual constructing the simultaneous regression equations.

Generally, the structural simultaneous model can be expressed as follows:

$$Y_{1t} = b_{12} \cdot Y_{2t} + \cdots + b_{1m} \cdot Y_{mt} + a_{11} \cdot X_{1t} + a_{12} \cdot X_{2t} + \cdots + a_{1n} \cdot X_{nt} + a_{10} + \xi_{1t} \quad (1)$$

$$Y_{2t} = b_{21} \cdot Y_{2t} + \cdots + b_{2m} \cdot Y_{mt} + a_{21} \cdot X_{1t} + a_{22} \cdot X_{2t} + \cdots + a_{2n} \cdot X_{nt} + a_{20} + \xi_{2t} \quad (2)$$

$$Y_{mt} = b_{m1} \cdot Y_{1t} + \cdots + b_{mm-1} \cdot Y_{m-1t} + a_{m1} \cdot X_{1t} + a_{m2} \cdot X_{2t} + \cdots + a_{mn} \cdot X_{nt} + a_{mt} + \xi_{mt} \quad (3)$$

The careful selection of exogenous and endogenous variables is methodologically undertaken to ensure a comprehensive understanding of their roles in the sustainable development of EU countries. Additionally, the correlation between the potential factor variables and the selected resulting indicators is assessed.

The designation of the number of students enrolled in higher education institutions (HEIs) as an endogenous variable for human capital in EU countries is justified by its capacity to quantify advancements in human capital quality. As students acquire valuable knowledge, develop hard and soft skills, and gain practical experience, these educational endeavours contribute to their subsequent engagement in economic activities. In the light of sustainability, such developments exert influence on employment and resource productivity by fostering social stability and instilling a responsible attitude towards the judicious use of limited resources. In other words, an increasing number of students enrolled in HEIs serves as an indicator of growing human capital.

The endogenous variable for the simultaneous regression equations is employment in the EU countries. The selection of this predicted variable is grounded in the perspective that employment dynamics established the conditions for involving human capital in economic activities and serve as a pivotal focal point for the pursuit of the SDGs.

The choice of resource productivity as the explained variable for assessing sustainable development is motivated by the shift towards actively incorporating resource-saving production in EU countries. Additionally, on a macroeconomic scale, resource productivity serves as an indicator reflecting the utilization conditions of available natural resources in the production of various economic goods, as well as the current state of technology and innovation.

4. The structural model of sustainable development in the EU countries

The simultaneous regression equations can be delineated by the following endogenous variables: Y_{1t} – students enrolled in tertiary education in the EU countries, number of individuals; Y_{2t} – total employment in the EU countries (resident population concept – LFS), from 20 to 64 years, thsd. people; Y_{3t} – resource productivity in the EU countries, euro per kilogram. The exogenous variables for the simultaneous model encompass the following: X_{1t} – gross domestic product at market prices in the EU countries, current prices, euro per capita; X_{2t} – average population in the EU countries, people; X_{3t} – total general government expenditures on tertiary education in the EU countries (levels 5–8), mln euro; X_{4t} – total environmental taxes in the EU countries, percent of gross domestic product (GDP); X_{5t} – employment with tertiary education in the EU countries (levels 5–8), from 15 to 64 years, number of individuals; X_{6t} – total environmental taxes, mln euro; X_{7t} – total general government expenditure on environmental protection in the EU countries, mln; X_{8t} – domestic extraction of material resources in the EU countries, tonnes per capita; X_{9t} – direct material inputs of fossil energy materials/carriers, tonnes per capita; X_{10t} – emigration by age in completed years, number of people.

The identified explained and explanatory variables included in the simultaneous model can be characterized through descriptive statistics (table 1). The data have revealed variations among the EU countries in the social and resource dimensions of sustainable development. In other words, this implies that the adoption of policy measures for sustainable development in the EU countries is differentiated and depends on each country's capacity to attain the SDGs.

To construct a set of simultaneous regression equations for human capital, employment dynamics, and resource productivity, statistical data from the Eurostat website [34] were utilized. The data were collected from 2013 to 2021 for the 26 EU countries. Consideration was given to the comprehensiveness of the statistical data provided for both the explained and explanatory variables. Specifically, for the endogenous variable Y_{1t}, statistical data for the year 2022 are not yet available for the sample EU countries. In essence, the simultaneous model comprises three regression equations based on an unbalanced panel dataset. In other words, each equation represents a pooled regression model without effects (fixed or random).

Table 1. Descriptive statistics for covariates of dependent and independent variables (based on [34]).

Variable	Mean	Scope of of variation	Standard deviation	Coefficient variation	Standard error
Y_{1t}	688169.3	3344785	831118.3	1.21	55042.2
Y_{2t}	7233.3	39754	9327.2	1.29	617.7
Y_{3t}	1.88	4.94	1.11	0.59	0.07
X_{1t}	31109.8	107280	21046.3	0.68	1393.8
X_{2t}	17359899	82872314	22158236.8	1.28	1467465
X_{3t}	4067.7	29344.9	5694.06	1.40	377.1
X_{4t}	2.57	2.98	0.65	0.25	0.04
X_{5t}	2477.6	12989.8	3178.8	1.28	210.52
X_{6t}	12203.9	64508.3	16978.9	1.39	1124.5
X_{7t}	4114.8	25950.8	6189.9	1.50	409.94
X_{8t}	17.02	62.35	12.31	0.72	0.824
X_{9t}	6.56	39.58	7.28	0.90	0.48
X_{10t}	97743.58	694438	124200.6	0.79	8225.4

The overall specification of the simultaneous model for the EU countries can be outlined as follows:

$$Y_{1t} = b_{13} \cdot Y_{3t} + a_{13} \cdot X_{3t} + a_{15} \cdot X_{5t} + a_{16n} \cdot X_{6t} + a_{110} \cdot X_{10t} + a_{10} + \xi_{1t} \tag{4}$$

$$Y_{2t} = b_{23} \cdot Y_{3t} + a_{22} \cdot X_{2t} + a_{23} \cdot X_{3t} + a_{24} \cdot X_{4t} + a_{20} + \xi_{2t} \tag{5}$$

$$Y_{3t} = b_{32} \cdot Y_{2t} + a_{31} \cdot X_{1t} + a_{37} \cdot X_{7t} + a_{38} \cdot X_{8t} + a_{39} \cdot X_{9t} + a_{30} + \xi_{3t} \tag{6}$$

In the reduced form, equations (4)–(6) can express in terms of the exogenous variables X_{jt} and the error terms e_{jt} and can write as:

$$Y_{1t} = \pi_{11} \cdot X_{1t} + \pi_{12} \cdot X_{2t} + \pi_{13} \cdot X_{3t} + ... + \pi_{19} \cdot X_{9t} + \pi_{110} \cdot X_{10t} + \pi_{10} + \upsilon_{1t} \tag{7}$$

$$Y_{2t} = \pi_{21} \cdot X_{1t} + \pi_{22} \cdot X_{2t} + \pi_{23} \cdot X_{3t} + ... + \pi_{29} \cdot X_{9t} + \pi_{210} \cdot X_{10t} + \pi_{20} + \upsilon_{2t} \tag{8}$$

$$Y_{3t} = \pi_{31} \cdot X_{1t} + \pi_{32} \cdot X_{2t} + \pi_{33} \cdot X_{3t} + ... + \pi_{39} \cdot X_{9t} + \pi_{310} \cdot X_{10t} + \pi_{30} + \upsilon_{3t} \tag{9}$$

where π_{ij} – reduced form parameters, υ_{ij} – reduced form errors, $i = (\overline{1,3})$, $j = (\overline{1,8})$.

The first equation (4) of the system delineates the number of students in the EU countries enrolled in tertiary education as a function of resource productivity, general budget expenditures on tertiary education, the employment of individuals with tertiary education, the total amount of environmental taxes, and the number of emigrants. The second equation (5) shows the functional dependence of employment in the EU countries on resource productivity, average population, general government expenditures on tertiary education, and environmental taxes by GDP. The third equation (6) in the structural model refers to the factors influencing the functional dependence of the resource productivity in the EU countries, specifically encompassing employment, GDP per capita, general budget expenditures on environmental protection, the volume of domestic extraction of material resources per capita, and direct material inputs of fossil energy materials/carriers per capita.

The structured equations system (4)–(6) can be presented in a tabular form to examine the model for identification criteria (table 2). The order conditions for the simultaneous equations have revealed that each of them is over-identified (table 3). In light of the verification results, it is recommended to employ a two-step least squares method to accurately assess the parameters associated with the over-identified simultaneous regression equations. This approach ensures a rigorous analysis of the model and enhances the reliability of the parameter estimation process.

Table 2. Tabular form of the simultaneous model.

a_{i0}	Y_{1t}	Y_{2t}	Y_{3t}	X_{1t}	X_{2t}	X_{3t}	X_{4t}	X_{5t}	X_{6t}	X_{7t}	X_{8t}	X_{9t}	X_{10t}
$-a_{10}$	1	0	$-b_{13}$	0	0	$-a_{13}$	0	$-a_{15}$	$-a_{16}$	0	0	0	$-a_{110}$
$-a_{20}$	0	1	$-b_{23}$	0	$-a_{22}$	$-a_{23}$	$-a_{24}$	0	0	0	0	0	0
$-a_{30}$	0	$-b_{32}$	1	$-a_{31}$	0	0	0	0	0	$-a_{37}$	$-a_{38}$	$-a_{39}$	0

Table 3. Conditions for the identification of the simultaneous equations.

The number of the equation, i	Number of excluded exogenous variables, $K - k_i$	Number of included endogenous variables reduced by 1, $m_i - 1$	Statement of possible identification
(4)	7	1	Over-identified equation
(5)	6	1	Over-identified equation
(6)	7	1	Over-identified equation

The simultaneous model elucidating dependencies among human capital, employment dynamics and resource productivity is as follows:

$$Y_{1t} = -39574.475Y_{3t} - 17.643X_{3t} + 165.271X_{5t} + 17.351X_{6t} + 1.260X_{10t} + 89829.312 + \xi_{1t} \quad (10)$$

$$Y_{2t} = -318.5286Y_{3t} + 0.000347X_{2t} + 0.3383X_{3t} + 417.0963X_{4t} + 1493.6708 + \xi_{2t} \quad (11)$$

$$Y_{3t} = -0.00004Y_{2t} + 0.000034X_{1t} + 0.000119X_{7t} - 0.0436X_{8t} + 0.0371X_{9t} + 1.1207 + \xi_{3t} \quad (12)$$

The coefficients of determination for each of the structural equations (10)–(12) show the existence of very strong correlations between exogenous and endogenous variables. The simultaneous model exhibits a noteworthy capacity to explain the change in the values of the explained variables, making it well-suited for predictive analysis. Each regression equation within the model satisfies the criteria stipulated by both the Fisher criterion and the Student's t-test, ensuring the adequacy of their representation (table 4). Furthermore, the absence of first-order autocorrelation, as assessed by the Durbin-Watson criterion, substantiates the model's statistical soundness. After delineating the structural parameters of the simultaneous model for human capital, employment dynamics, and resource productivity in EU countries, it is imperative to undertake a judicious interpretation of these equations.

5. The interpretation of the simultaneous model for sustainable development in the EU countries

In line with equation (10) of the simultaneous model, it is posited that the number of students enrolled in tertiary education in the EU countries is influenced by resource productivity, total general government expenditures on tertiary education, the number of employed people with

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Table 4. The simultaneous equations model and reporting regression results (based on [34]).

Variables	Intercept and slope	Standard error*	t-statistic	p-level, $p < 0.05$	Confidence interval, 95% low-level	Confidence interval, 95% high-level	DW, 99%
Y_{1t}-meet	89829.31	15819.81	5.678	0.000	58653.1	121005.5	1.953
Y_{3t}	–39574.48	8165.775	–4.846	0.000	–55666.8	–23482.1	$d_L=$
X_{3t}	–17.643	3.057	–5.773	0.000	–23.666	–11.620	1.633
X_{5t}	165.271	8.014	20.623	0.000	149.478	181.064	$d_U=$
X_{6t}	17.351	1.061	16.350	0.000	15.260	19.443	1.715
X_{10t}	1.260	1.128	9.822	0.000	1.007	1.513	
Regression statistics			Analysis of variance				
R	0.9909		df	SS	MS	F	p-level
R^2	0.9819	Regression	5	$1.54\cdot10^{14}$	$3.08\cdot10^{13}$	2505.876	0.000
Adj. R^2	0.9815	Residual	222	$2.84\cdot10^{12}$	$1.28\cdot10^{10}$		
St. error**	113131.443	Total	227	$1.57\cdot10^{14}$			
Y_{2t}-meet	1493.671	178.434	8.371	0.000	1142.038	1845.303	1.955
Y_{3t}	–318.529	37.174	–8.569	0.000	–391.787	–245.271	$d_L=$
X_{2t}	$3.47\cdot10^{-4}$	3.00·10–6	110.639	0.000	$3.41\cdot10^{-4}$	$3.54\cdot10^{-4}$	1.633
X_{3t}	0.338	0.013	26.832	0.000	0.314	0.363	$d_U=$
X_{4t}	–417.096	58.953	–7.075	0.000	–533.273	–300.919	1.715
Regression statistics			Analysis of variance				
R	0.9982		df	SS	MS	F	p-level
R^2	0.9964	Regression	4	$1.97\cdot10^{10}$	$4.92\cdot10^{9}$	15377.99	0.000
Adj. R^2	0.9963	Residual	223	$7.13\cdot10^{7}$	$3.20\cdot10^{5}$		
St. error**	565.585	Total	227	$1.98\cdot10^{10}$			
Y_{3t}-meet	1.121	0.048	23.059	0.000	1.025	1.217	2.068
Y_{2t}	$-4.00\cdot10^{-5}$	5.00·10–6	–7.759	0.000	$-5.00\cdot10^{-5}$	$-3.00\cdot10^{-5}$	$d_L=$
X_{1t}	$3.40\cdot10^{-5}$	$1.00\cdot10^{-6}$	32.408	0.000	$3.20\cdot10^{-5}$	$3.60\cdot10^{-5}$	1.633
X_{7t}	$1.19\cdot10^{-4}$	$8.00\cdot10^{-6}$	14.717	0.000	$1.03\cdot10^{-4}$	$1.34\cdot10^{-4}$	$d_U=$
X_{8t}	–0.044	0.0023	–19.196	0.000	–0.048	–0.039	1.715
X_{9t}	0.037	0.004	9.324	0.000	0.029	0.045	
Regression statistics			Analysis of variance				
R	0.9646		df	SS	MS	F	p-level
R^2	0.9305	Regression	5	259.793	51.959	594.796	0.000
Adj. R^2	0.9290	Residual	222	19.393	0.0874		
St. error**	0.296	Total	227	279.186			

* – the slope parameters and intercept;
** – the regression.

tertiary education, and the amount of environmental taxes to the extent of 98.18%. Anticipating changes in these factors provides valuable insights into their impact on the average number of students enrolled in tertiary education (levels 5–8) in the EU countries.

Specifically, an increase of 1 euro/kg in resource productivity in the EU countries is associated with an estimated decrease of 39,574.5 in the average number of students enrolled in tertiary education (levels 5–8). Conversely, a reduction of 1 million euros in the total general government expenditures on tertiary education (levels 5–8) in the EU countries is linked to a decrease of 17.6 in the average number of students enrolled in tertiary education (levels 5–8). Moreover, an increase of 1 person in the number of employed people with tertiary education in the EU countries corresponds to anticipated growth of 165.3 in the average number of students enrolled in tertiary education (levels 5–8). Furthermore, an augmentation of 1 million euros in the volume of environmental taxes is associated with an expected increase of 17.4 in the average number of students enrolled in tertiary education in the EU countries. If the number of emigrants increases by 1 individual, it is expected that the average number of students in the EU countries enrolled in tertiary education may increase by 1.3. These findings provide insights into the complex dynamics governing the enrolment patterns in tertiary education across the EU countries, shedding light on the nuanced influence of key variables within the model.

However, since February 24, 2022, human capital in the EU countries has been affected by the war in Ukraine, resulting in forced migration for temporary protection. Between July 2022 and March 2024, the average monthly growth rate of temporary protection beneficiaries from Ukraine was 102.4%. Of these beneficiaries, 101.4% were under the age of 18, 102.7% were aged 18-34, 103.0% were aged 35-65, and 103.7% were aged over 65 [calculated based on [34]]. Concerning age structure, 34.3% of Ukrainians are under the age of 18, 24.0% are aged 18-34, 35.1% are aged 35-65, and only 5.9% are over 65 [calculated based on [34]]. Essentially, a significant proportion of economically active individuals people and young people under the age of 18 from Ukraine have sought refuge in the EU countries. In the long run, under the most pessimistic possible scenario for Ukraine, the EU countries stand to benefit from the influx of human capital, which could either be enhanced in quality through education or actively participate in the labour market. Nonetheless, determining the relationship between EU human capital, forced migration from Ukraine and other factors is challenging due to Eurostat's recent initiation of compiling statistics on temporary protection beneficiaries from Ukraine.

As indicated by the parameters of equation (11) within the simultaneous model, there is a 99.64% probability that the total employment of the population aged 20–60 in the EU countries, as per the resident population concept is influenced by several factors, including resource productivity, the average population of the country, total general government expenditures on tertiary education (levels 5–8), and the structure of general environmental taxes. These factors collectively account for the variation in total employment to a substantial degree.

The analysis reveals that an increase of 1 euro/kg in resource productivity may result in an estimated decrease of 318.5 thousand people in the average total employment of the population aged 20–60 years in the EU countries, adhering to the resident population concept. Instead, a rise in the average population in the EU countries by 10,000 people is associated with an anticipated increase of 3.5 thousand people in the average total employment of the population aged 20–60 in these countries, considering the resident population concept. Furthermore, an increase of 1 million euros in the total general government expenditures on tertiary education (level 5–8) in the EU countries may lead to a potential increase of 0.3 thousand people in the total employment of the population aged 20–60 in these countries, based on the resident population concept. Additionally, an increase of 1% in the total environmental taxes in the EU countries is linked to an expected decrease of 417.1 thousand people in the average total employment of the population aged 20–60, according to the resident population concept. These findings underscore the intricate dynamics governing the relationship between various factors and total employment within the specified age group in the EU countries, providing nuanced insights for both academic and policy considerations.

On the basis of equation (12) of the simultaneous model, it is posited that resource productivity in the EU countries is significantly influenced by several factors, encompassing 93.5% of the total variance. The determinants include the total employment of the population aged 20–60 years according to the resident population concept, GDP in market prices per capita, total general government expenditure on environmental protection, domestic extraction of material resources per capita, and direct material inputs of fossil energy materials/carriers per capita. Foreseeing alternations in these factors provides valuable insights into their potential impact on the average resource productivity in the EU countries.

In particular, an increase of 10,000 thousand people, according to the resident population concept, is associated with an expected decrease of 0.40 euros/kg in the average resource productivity in the EU countries. Meanwhile, an increase of 10,000 euros per capita in the GDP in market prices may lead to an increase of 0.34 euros/kg in the average resource productivity in the EU countries. Moreover, an increase of 10,000 million euros in the total government budget expenditures on environmental protection in the EU countries is linked to an estimated increase of 1.19 euros/kg in the average resource productivity. Additionally, an increase of 1 tonne per capita in domestic extraction of material resources in the EU countries corresponds to an anticipated decrease of 0.0436 euros/kg in the average resource productivity. If the direct material inputs of fossil energy materials/carriers in the EU countries increased by 1 tonne per capita, the average resource productivity could rise by 0.0371 euros per capita. These findings contribute to a comprehensive understanding of the complex dynamics influencing resource productivity in EU countries, offering insights into the potential impacts of various economic and environmental factors.

By comparing the theoretical and empirical values of endogenous variables within the structural equations system for individual countries of the EU, an examination of the quality of the simultaneous model can be conducted by calculating the forecast accuracy metrics for selected EU countries (table 5). Given this fact, the simultaneous model as represented by regression equations (10)–(12), accurately reflects the dependencies among human capital, employment dynamics, and resource productivity for sustainable development in selected EU countries. The forecast accuracy indicators for variables Y_{1t}, Y_{2t}, and Y_{3t} for all analyzed countries are less than 10%, underscoring the high accuracy of theoretical values. However, for Y_{1t} and Y_{3t} in Austria, the values of MAPE and RMSPE exceed 10%, indicative of a still acceptable but comparatively lower forecast accuracy. Furthermore, the U-statistic values for the endogenous variables Y_{1t}, Y_{2t}, and Y_{3t} are in proximity to 0, affirming the accuracy of the theoretical values calculated for Austria, Belgium, and Portugal. This analysis highlights the robustness of the simultaneous model, implying its effectiveness in capturing and predicting the complex relationships among human capital, employment, and resource productivity in the EU countries, with a specific focus on sustainable development.

Based on the specified parameters outlined in structural equations (10)–(12), the theoretical values of the endogenous variables Y_{1t}, Y_{2t}, and Y_{3t} for selected EU countries, specifically Austria, Belgium, and Portugal can be calculated and subsequently compared with empirical values. Figures 1–3 present the dynamics of both empirical and theoretical values for the endogenous variables Y_{1t}, Y_{2t}, and Y_{3t} in Austria, Belgium, and Portugal. Given this fact, the theoretical values, derived from the simultaneous model, exhibit fluctuations in the number of students, employment and resource productivity, indicating instances where they may surpass or lag behind empirical data. For the attainment of SDGs in the EU countries, it is imperative to sustain the positive dynamics in terms of the number of students, employment, and resource productivity. The disparities between theoretical and empirical values underscore the complexity of these relationships and emphasize the need for ongoing analysis and adaptation of policies to

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Table 5. Assessment of theoretical values for endogenous variables in the simultaneous equations model (calculated based on [34] and equations (10)–(12)).

Dependent variable	Forecast accuracy metrics	Austria	Belgium	Portugal
Y_{1t}	Mean absolute percentage error (MAPE), %	6.08	9.35	2.38
	Root mean square percentage error (RMSPE), %	10.66	9.88	5.46
	Theil's Forecast Accuracy Coefficient (U)	0.0543	0.0475	0.0276
Y_{2t}	Mean absolute percentage error (MAPE), %	6.18	3.05	5.80
	Root mean square percentage error (RMSPE), %	6.47	3.81	8.51
	Theil's Forecast Accuracy Coefficient (U)	0.0334	0.0183	0.0452
Y_{3t}	Mean absolute percentage error (MAPE), %	10.95	3.59	2.93
	Root mean square percentage error (RMSPE), %	11.11	6.97	3.89
	Theil's Forecast Accuracy Coefficient (U)	0.0598	0.0396	0.0183

foster sustainable development.

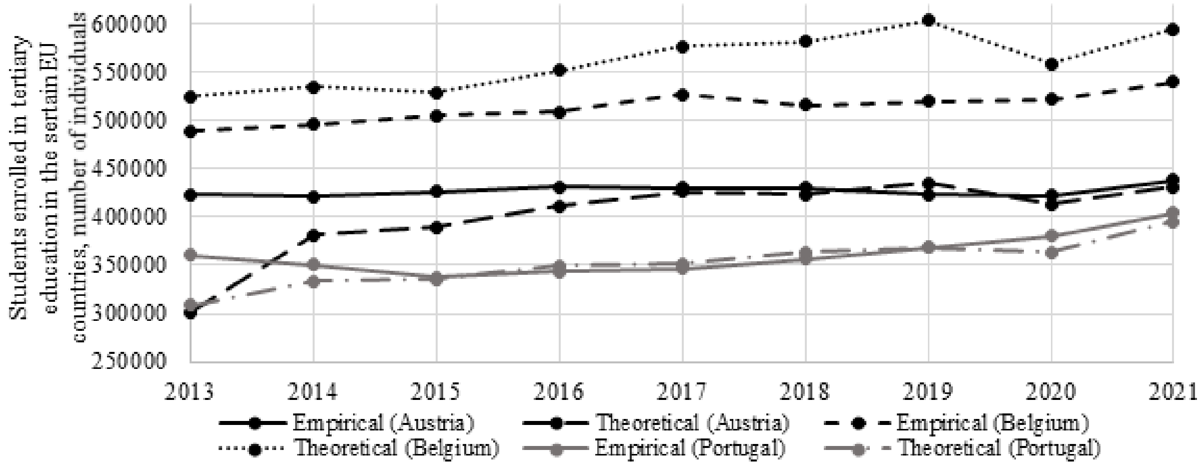

Figure 1. Actual and predicted dynamics of students enrolled in tertiary education in certain EU countries.

6. Conclusions

To summarize, the construction of the simultaneous model, comprising three regression equations, provides valuable insight into the complex dependencies among human capital, employment dynamics, and resource productivity in the EU countries from the standpoint of sustainable development. In this model, human capital in the EU countries is conceptualized as a function of the number of students enrolled in tertiary education. This dependence is contingent upon explanatory variables such as resource productivity, general government expenditures on tertiary education, employment of the population with tertiary education, total environmental taxes, and the number of emigrants.

Employment in the EU countries is delineated by the function of the total employment of the population aged 20–64, based on the resident population concept. It is influenced by resource productivity, average population, general government spending on tertiary education, and the share of environmental taxes in GDP. Additionally, the environmental dimension of

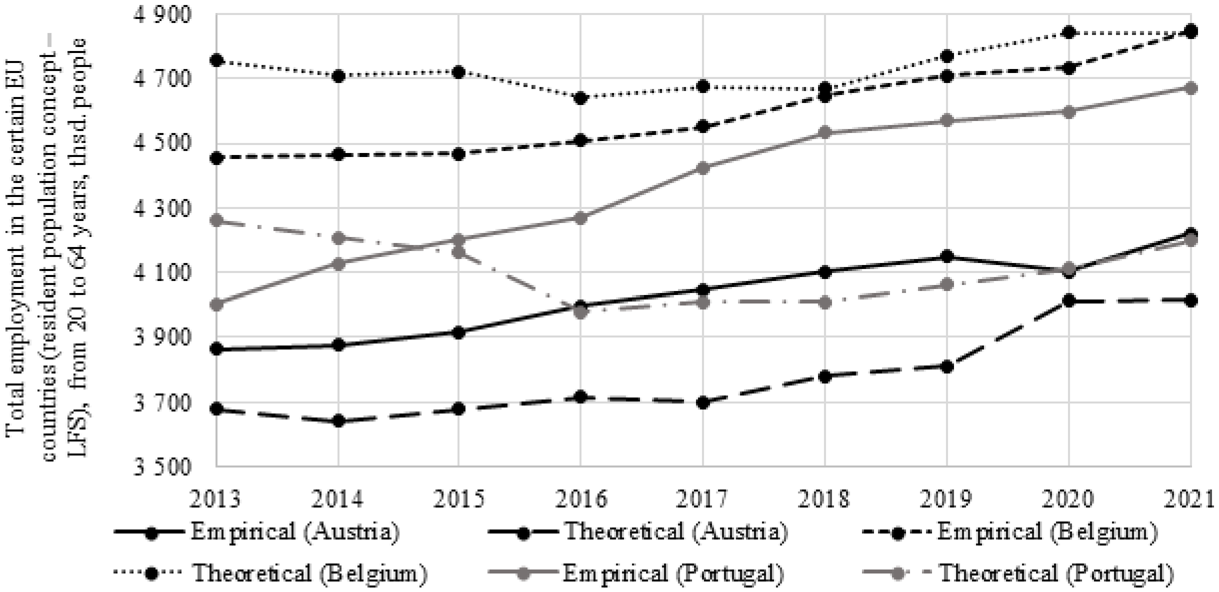

Figure 2. Actual and predicted dynamics of total employment in certain EU countries.

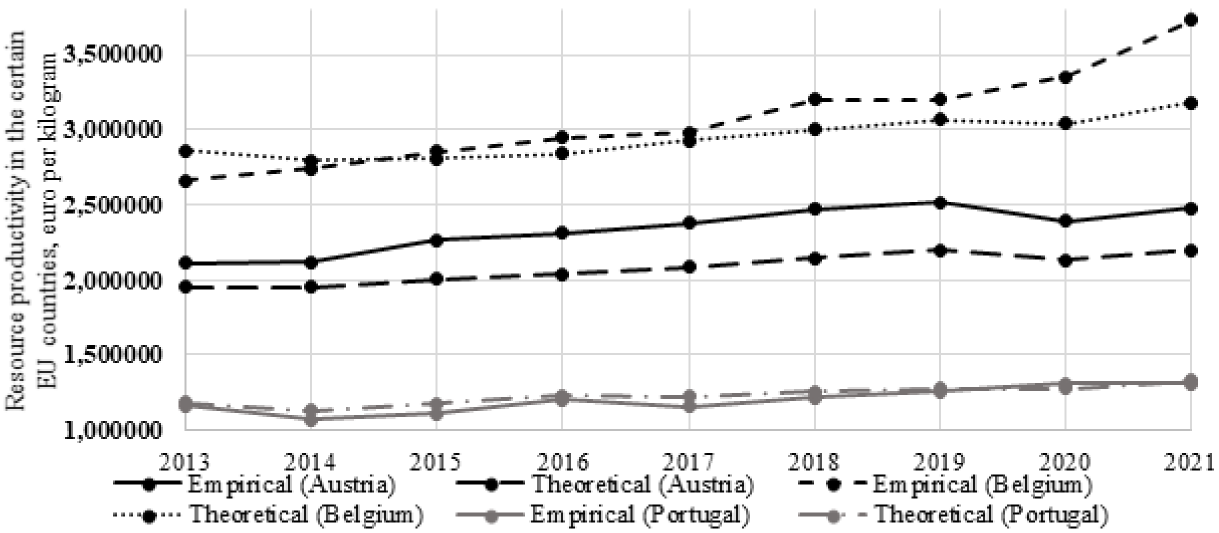

Figure 3. Actual and predicted dynamics of total employment in certain EU countries.

sustainable development is represented through resource productivity in the EU countries. This explained variable functionally depends on the total employment among the population aged 20–64 according to the resident population concept, GDP per capita at market prices, general government expenditures on environmental protection, local extraction of material resources per capita, and the volume of direct material inputs of fossil energy materials/carriers per capita. Additionally, theoretical and empirical figures for the endogenous variables of the simultaneous model were constructed and compared for certain EU countries, providing a basis for evaluating the regression equations' quality. This also confirms the accuracy of the variables selection as well as the description of dependencies among them.

In line with the parameters of the structural equations, the enhancement of human capital for sustainable development in the EU countries hinged upon strategies related to the public funding of tertiary education, the employment scenario for people with tertiary education, determinants of resource productivity, and the volume of environmental taxes. The employment landscape, considered as a crucial dimension of sustainable development in the EU countries, will be shaped by demographic conditions, policy measures aimed at bolstering resource productivity, improvements in the state's capacity to fund tertiary education, and evolving strategies concerning general environmental taxation. The enhancement of the environmental dimension within the EU's sustainable development framework hinged on several factors. These include the features of employment and GDP, government expenditures on environmental protection, the intensity of material resource extraction, and the increase in direct material inputs from fossil energy resources.

Undoubtedly, the war in Ukraine will also exert an impact on the sustainable development in the EU countries. Concerning human capital, this impact will be driven by the integration of forced migrants into recipient countries' economies and the formation of their expectations regarding a potential return to Ukraine following the cessation of hostilities. It is conceivable that some of the forced migrants from Ukraine will engage in educational pursuits, including higher education. Regarding employment in EU countries, this may entail the integration of certain forced migrants from Ukraine into various sectors of the recipient country's economy following an adaptation period. As for the resource productivity in the EU countries, the war in Ukraine may serve as a catalyst for more efficient utilization of local material resources and reduced reliance on fossil energy resources. Additionally, Russian military aggression has had catastrophic repercussions for human capital, the labour market, and the environment in Ukraine, creating substantial barriers to sustainable development.

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Development of dephosphorization technology for iron ores with high phosphorus content

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Development of dephosphorization technology for iron ores with high phosphorus content

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Abstract. The main methods of removing phosphorus and sulfur from iron ores, as well as magnetite and hematite concentrates, were analyzed. For effective dephosphorization of hematite concentrates, it is necessary to use direct cationic flotation of apatite, with the help of which it is possible to remove more than 74% of phosphorus from the concentrate. As a result of the analysis of the conducted research and the synthesis of the obtained scientific results, a technology was developed for removing phosphorus from iron concentrates. This technology allows for the reduction of the phosphorus content from 0.14% to 0.04%. Chemical methods – alkaline or acid leaching with separation of the leached concentrate – are the most common ways to dephosphorylate metal-containing ores. Research on chemical methods of cleaning ores and iron ore concentrates is carried out in the following directions: leaching with alkali solutions; acid leaching at different temperatures; and leaching of impurities in autoclaves. The conditions of leaching of poor hydrogethite high-phosphorus concentrates at high and low temperatures were investigated. The proposed technology of leaching samples of poor hydrogethite high-phosphorus concentrates at high and low temperatures allows us to claim that the parameters of the firing process allow the recrystallization of iron and therefore contribute to the access of mineral acid to particles containing phosphorus.

1. Introduction

Currently, Ukraine is the seventh largest producer of iron ore raw materials in the world with a state balance of ores in the amount of about 30 billion tons, which are concentrated in 52 deposits, 24 of which are currently being developed [1]. The analysis of the practical experience of beneficiation of magnetite ores at mining and beneficiation factories in Ukraine (more than 70 years) made it possible to establish a clear relationship between the beneficiation indicators of non-oxidized quartzites and their composition by comparing the results of beneficiation of quartzites according to their material composition and structural [2].

Nowadays, 98.5% of iron ore products are used for the needs of ferrous metallurgy, so the requirements for the quality of the mineral-raw material base come from the requirements for steel, and cast iron, as well as from the technological features of steelmaking production [3]. Since the blast furnace is the main technological process in Ukraine and Eastern Europe, the requirements for the quality of iron ore products are primarily focused on it. It should be noted that the requirements for the quality of iron ore products exported to Western Europe are higher since the metallurgical production of industrialized countries is focused primarily on the direct recovery of iron, bypassing the blast furnace process. Therefore, the main task is to provide the iron mining industry with high-quality mineral raw materials suitable for high-quality metallurgy [4, 5]. This is possible due to the improvement of the technology in the development of operational objects [6, 7].

Phosphorus is a harmful impurity in metal, because, being in it, it gives it brittleness and greatly increases the tendency to brittle fracture. Phosphorus also increases the cold-brittleness threshold, that is, the temperature at which the impact viscosity drops sharply. Since phosphorus cannot be easily removed from the flux or melt, the maximum allowable content of phosphorus in steel is limited to a rather low limit, which, taking into account the requirements for the metal and the possibilities of dephosphorization, is up to 0.02-0.04%.

A large amount of damage in the smelting of iron and ferromanganese is caused by an excess of silica. When smelting iron, increasing the silica content by 1% increases the consumption of coke by approximately 3%, fluxes by 4%, and reduces the productivity of the blast furnace by 2-7%. When smelting ferromanganese, silica leads to the formation of strong manganese silicates in the lower part of the furnace, which turns into slag, which, in turn, sharply reduces the extraction of manganese.

In the recovery process of either the ore or the production concentrate, the empty rock contained in the metal pellets is transformed into the final product. In addition, the presence of empty rock in metalized raw materials causes a large slag formation in the steel smelting process. Under these conditions, the consumption of electricity and fluxes increases significantly, and the duration of melting increases. In addition, slag corrodes the lining of furnaces. Therefore, in the metalized raw materials intended for steel smelting, they strive to reduce the content of empty rock as much as possible and to bring the content of acidic rocks (SiO_2) to 4%.

Therefore, the creation of a fairly simple and effective technology for the preparation of magnetite and hematite concentrate, which ensures a reduction in the content of harmful impurities, is a very urgent practical task.

2. Literature review

Depending on the composition of iron ores, technologies for their enrichment and further preparation for metallurgical redistribution are being developed. Preparation of iron ore concentrates for metallurgical redistribution includes calcination, cooling, leaching with mineral acid, separation of the liquid phase from the solid phase, and so on. All this leads to an improvement in the quality of iron ore concentrates, because at the same time unwanted impurities contained in the concentrates, primarily phosphorus, sulfur, and arsenic, are eliminated. Metallurgical methods of phosphorus removal from concentrates are mainly used.

So, the firing process is carried out at a temperature of 800-1000ºC. At the same time, the structure of hydrogethite (FeOOH) is destroyed, and the recrystallization of iron and displacement of phosphorus from grains at the interface of phases (crystals) occurs.

At a temperature below 800ºC, the process proceeds with insufficient completeness. At temperatures above 1000ºC, particles sinter into agglomerates and acid access to phosphorus-containing mineral particles deteriorates, as a result of which the degree of phosphorus extraction decreases.

The firing time within 1 hour ensures a high extraction of phosphorus into the solution during further leaching. An increase in the firing time, of more than one hour, worsens the technical and economic indicators of the entire dephosphorization process. A process combining oxidative calcination-gas reduction and magnetic separation has been developed for iron dephosphorylation at a lower reduction temperature [8].

Studies based on the possibility of redistribution of phosphorus from ore components to slag-forming ones in the process of agglomerate firing have been conducted [8].

Disadvantages of metallurgical methods of dephosphorization include their uneconomical nature, large losses of iron (up to 20%), and environmental problems.

The problem of developing a technology for removing phosphorus by non-metallurgical means and obtaining a phosphorus-conditioned concentrate from these ores is of great practical interest and is of great importance for many countries of the world, such as Australia, Spain, Colombia, the USA, Sweden, France, and others. Part of phosphorus is part of the cement mass, which binds finely dispersed magnetite grains. Therefore, it is impossible to remove it by mechanical means to a mass fraction that meets the requirements of metallurgical redistribution. Fairly limited removal of phosphorus is achieved by grinding and magnetic separation.

The focus of current research and development in the field of flotation is cationic and anionic flotation methods from the point of view of reagent regimes, pulp chemical composition, and particle size, as well as the efficiency of removing major impurities such as silica, alumina, phosphorus, and sulfur [9]. Anionic reagents are usually used to remove phosphorus by flotation methods. Thus, the Aqua Nobel company developed a cationic reagent based on the Lilaflot reagent, the use of which during flotation at a flow rate of about 70 g/t made it possible to remove 90-95% of the phosphorus contained in this concentrate from the magnetite concentrate. At the same time, the loss of iron was about 2%.

A method of direct flotation of phosphate minerals from magnetite concentrates has been developed, in which the pulp is treated with an alkaline agent to pH from 7 to 11 and a depressor of carbonate and silicate minerals. A collector type of succinic acid derivatives is introduced in the amount from 20 to 2000 g/t of the initial product and a foaming agent [10].

Periodic flotation tests of an effective combination of reagents to reduce the content of silica and phosphorus in iron concentrate were carried out. The study aimed to study the influence of dosage, sodium silicate module, and the addition of Ca++ ions on the selectivity of separation of phosphorous and siliceous vein minerals from iron oxides [11].

The disadvantage of flotation methods for cleaning iron ores from phosphorus is the impossibility of their removal from finely dispersed growths. Therefore, in this case, hydrometallurgical methods are used.

Consider the use of hydrometallurgical methods for removing phosphorus from iron ores.

The method of pre-treatment of ore to reduce the content of sulfur and phosphorus in it by washing the ore (essentially iron oxides) with aqueous solutions of soda with a gradual increase in temperature, includes mixing an inorganic base with oxide iron ore, which mainly contains iron oxides at a ratio of approximately $0.1 \div 1.5$ – bases to the weight of iron ore; heating the mixture to 300^{o}C and rinsing the mixture with hot water.

The disadvantages of this method include the fact that the degree of reduction of phosphorus impurities in the ore remains low and, therefore, does not allow obtaining conditioned iron ore concentrates.

Recently, the most common methods of dephosphorylation of metal-containing ores are chemical methods – alkaline or acid leaching with separation of the leached concentrate [12]. In the case of hematite ores, heat treatment is necessary before alkaline or acid leaching to make phosphorus available for chemical separation [9, 13]. The amount of phosphorus removed increases with heating temperature up to 1300°C. Silica, alumina and sulfur are usually removed along with phosphorus. Chemical methods of cleaning ores and iron ore concentrates are used in different versions. Research is mainly carried out in the following areas:

- leaching with alkali solutions;
- acid leaching at different temperatures;
- leaching of impurities in autoclaves.

When choosing a method of chemical enrichment, it is necessary to be guided by the availability of reagents, profitability, and a sufficient degree of purification.

Removal of silicon compounds is possible with alkali solutions. Acids are used to remove calcium and magnesium.

There is a known method of removing phosphorus from Lorraine iron ore, which contains 30% Fe, 20% SiO_2, 7% Al_2O_3 and 1.7% P_2O_5, which involves treating the ore with a 40-50% alkali solution at a temperature of 125-140^oC, duration from 30 min to 3 hours and the amount of solids in the pulp from 50 to 200 g/l. At the same time, up to 60-80% of phosphorus, silica, and other ore minerals were extracted into the solution, while more than 93-95% of iron was extracted into the concentrate.

In this method, the most common is sodium hydroxide. But when it is used, there are non-technological solutions that are poorly defended and filtered. In addition, the discovered optimal leaching regime has several serious drawbacks: a complex scheme of alkali regeneration and significant water consumption for its washing.

A complex method of beneficiation of iron ore using NaOH and magnetic separation has been tested in the USA. It includes the following stages:

(i) mixing ore or ordinary concentrate with a small volume of diluted NaOH solution;
(ii) treatment of the mixture with superheated steam at a temperature of 260-400^oC.

Such processing leads to the fact that the bonds between SiO_2 crystals, as well as between SiO_2 and iron minerals are weakened. There is other evidence that chemical treatment (alkaline or acid) of iron ore concentrates containing quartz and iron silicates alters the surface properties of the minerals, which improves flotation and magnetic re-separation performance. When ordinary hematite concentrates obtained from ores of the Kryvyorizhye deposit were treated with NaOH solution, the silicon content decreased from 8.62 to 0.76%. Phosphorus, sulfur and arsenic were leached to hundredths of a percent. The content of calcium and magnesium increases after alkaline treatment. At the same time, sulfur goes into solution in the form of sulfates according to the equation: $FeS_2 + 16NaOH + 15O_2 \rightarrow 4Fe(OH)_3 + 8Na_2SO_4 + 2H_2O$.

Acid treatment of iron ores is carried out in order to separate impurities of phosphorus, arsenic, sulfur, calcium, and magnesium. According to research, any mineral acid at a temperature of 70^oC removes arsenic from ores from the above-mentioned impurities, such acids as sulfate H_2SO_4 and chlorine HCl are used.

Many studies have been conducted on the purification of iron ores with nitric acid. Most of the works were carried out by Japanese researchers. A method of separating impurities from iron ore with concentrated nitric acid was patented in Japan, which ensured an increase in the iron content from 55 to 65% due to the complete leaching of phosphorus and arsenic and partially – calcium, magnesium, manganese, and sulfur.

In further studies, the concentration of nitric acid was reduced without reducing the leaching efficiency by increasing the temperature adding sulfuric acid to nitric acid, or conducting the leaching process at 200^oC in an autoclave.

Acids, as you know, interact with iron compounds, which leads to additional consumption of acids and a decrease in the yield of the concentrate. But in all patents, these disadvantages of acid enrichment are ignored. It should also be noted that acid regeneration is impossible. After leaching, the alkali can be regenerated by adding lime.

The method of oxidative leaching in an acidic environment of complex iron ores consists of processing the material under such conditions as to promote the oxidation of iron and sulfur, to oxidize sulfur sulfide, at least partially, into sulfate [14,15]. Oxidized iron and impurities go into the solution in the leaching process, which is carried out over a certain period until more than 80% of the sulfide contained in the material is oxidized. At the same time, leaching sediment is formed, which is suitable for the thermometallurgical recovery of iron. This method gives a positive result for sulfur removal but does not provide dephosphorization of iron ore.

The method of leaching phosphorus with sulfuric acid at a temperature of 95-100ºC is also known. The consumption of sulfuric acid to dissolve phosphorus contained in concentrates is 30 kg per 1 kg of leached phosphorus, i.e. much higher than stoichiometry. To avoid re-precipitation of ferric sulfate, it is necessary to operate with pH values in the range of 1.6-1.4, depending on the content of solid particles in the pulp. The ratio of solid to liquid (S÷L) should be 1÷2-1÷3, and the total leaching time should be 50 minutes. Further processing of the concentrate is carried out by the method of pelleting and firing of the obtained pellets. At the same time, the content of sulfur decreases by 95%, and phosphorus – by approximately 80% [15].

The disadvantage of this method is the complexity of the technological design of the leaching process, the high temperature of the process, and the large losses of iron with solutions.

Hydrochloric acid can also be used as a mineral acid during leaching. The essence of the method is that iron ore is first agglomerated, and then leached using hydrochloric acid or gaseous hydrogen chloride. The leaching temperature is 90-105ºC.

The method of selective acid leaching was used to remove phosphorus from iron ores with a high phosphorus content. Hydroxyapatite in iron ores with a high phosphorus content was converted to soluble phosphate in the process of HCl leaching. The effect of reaction time, particle size, concentration of hydrochloric acid, reaction temperature, liquid-solid ratio, and stirring power on the degree of dephosphorylation was studied [16].

The disadvantage of this method is that it uses volatile hydrochloric acid, which is very harmful to service personnel and leads to equipment corrosion due to the presence of hydrogen chloride.

It should be noted that chemical leaching is successful only if it is preceded by heat treatment, which causes recrystallization of iron minerals in L–Fe_2O_3 and concentrated phosphorus between hematite grains. Heat treatment consists of burning the concentrate at a temperature of 500-600ºC for 1-1.5 hours, and for leaching, sulfuric acid is used in an amount of at least 110-150% of the stoichiometric about phosphorus, at a temperature of 60-80ºC, the ratio S÷L = 1÷3-1÷5. The leaching time is 2-3 hours.

A known method of cleaning iron ore from arsenic and phosphorus, in which the ore, crushed to 0.05-0.50 mm, was treated with a 0.5-2% solution of sulfuric acid at a high ratio of liquid to solid phases for 10-20 hours with subsequent ion exchange removal of impurities from the solution.

The disadvantages of this method are the long duration of the process (25 hours) and a significant amount of liquid phase, which requires a large volume of equipment.

The speed of all physicochemical heterogeneous processes increases with increasing temperature. When the leaching of impurities is carried out in autoclaves. At the same time, alkali solutions with concentrations of 40-50% are used in autoclaves at a temperature of 124-140ºC, or sulfuric acid with a concentration of 60-70% at 95-100ºC. The use of autoclaves allows you to maintain the temperature of the process above the boiling point of the solution. This leads to more efficient leaching.

3. Research objectives and approach

The primary objective of this research was to develop effective technologies for dephosphorization of various iron-containing concentrates, including magnetite, hematite, and hydrogethite, to reduce phosphorus content to levels meeting global quality requirements for iron ore products.

Specific aims of the study included:

1. Characterize the mineralogical composition and phosphorus distribution in magnetite-hematite ore samples and concentrates.
2. Evaluate desliming as a method to reduce phosphorus in magnetite concentrates.

3. Investigate direct flotation techniques, both anionic and cationic, for phosphorus removal from hematite concentrates.
4. Examine high and low temperature acid leaching processes for dephosphorization of hydrogethite concentrates.
5. Develop an integrated dephosphorization technology applicable to different types of iron ore concentrates.

The research approach involved detailed mineralogical analysis, laboratory-scale beneficiation and flotation experiments, and leaching tests under various conditions. Multiple dephosphorization techniques were evaluated to determine the most effective methods for different ore types. The ultimate goal was to achieve phosphorus reduction to below 0.05% in the final iron ore products, meeting stringent international quality standards.

4. Results

At the first stage of the research, a sample of magnetite-hematite ore with a mass fraction of iron of 53.8% was received. As a result of magnetic separation, two concentrates were obtained: magnetite (yield 47.7%, Fe_{total} mass fraction 69.509%) and hematite (yield 15.27%, Fe_{total} mass fraction 60.48%). The yield of tails was 37.03%. Iron losses by magnetic technology amounted to 21.2%. As you can see, the concentrates meet the requirements of the metallurgical industry in terms of the mass fraction of iron. However, it should be noted that they have a high mass fraction of phosphorus – 0.071 and 0.343%, respectively, in magnetite and hematite concentrates. Therefore, research on dephosphorylation was carried out precisely on samples of these concentrates. Note that a larger mass fraction of phosphorus is characteristic of hematite concentrate, because it has a smaller size compared to magnetite.

As a result of the study of the mineralogical composition of the concentrates, it was established that calcite is present in all the studied products – a violent reaction with acid. Non-ore minerals are observed in the form of both free fragments and in the form of inclusions with ore minerals. A characteristic feature of the studied magnetite and hematite concentrate is also a sharp dispersion of the dimensions of the fragments. The smallest fragments are mainly represented by iron hydroxides, calcite, and apatite. Apatite is represented by elongated as well as short-prismatic individuals. It most often spatially tends to calcite, but it is emphasized in the form of small inclusions in magnetite. The size varies widely from units of micrometers to tenths of a millimeter (figure 1).

On the basis of the analysis of the results of the study of the material composition, chemical and mineralogical properties of magnetite and hematite concentrates and the properties of apatite, we came to the conclusion about the feasibility of descaling magnetite concentrates and direct flotation of apatite from hematite concentrates.

Descaling was carried out on a sample of magnetite concentrate. The purpose of desliming was to reduce the mass fraction of phosphorus in the sample due to the removal of the minus 0.02 mm grade, where finely divided apatite is mainly concentrated. The results of magnetite concentrate de-slagging are shown in figure 2.

The obtained data confirm the expediency of the de-sludging operation in the technological scheme of beneficiation of rich hematite-magnetite ores. Thus, it was possible to reduce the mass fraction of phosphorus in the concentrate by 2.37 times – from 0.071 to 0.03%, which meets international standards for the quality of magnetite concentrate. which meets international standards for the quality of magnetite concentrate [17]. As a result of the descaling of the magnetite concentrate, the mass fraction of total iron in the concentrate also increased by 0.01%.

In the second stage of research, studies on direct anionic flotation of apatite were conducted on a sample of hematite concentrate. Distilled tall oil soap (DTOS) was used as an anionic

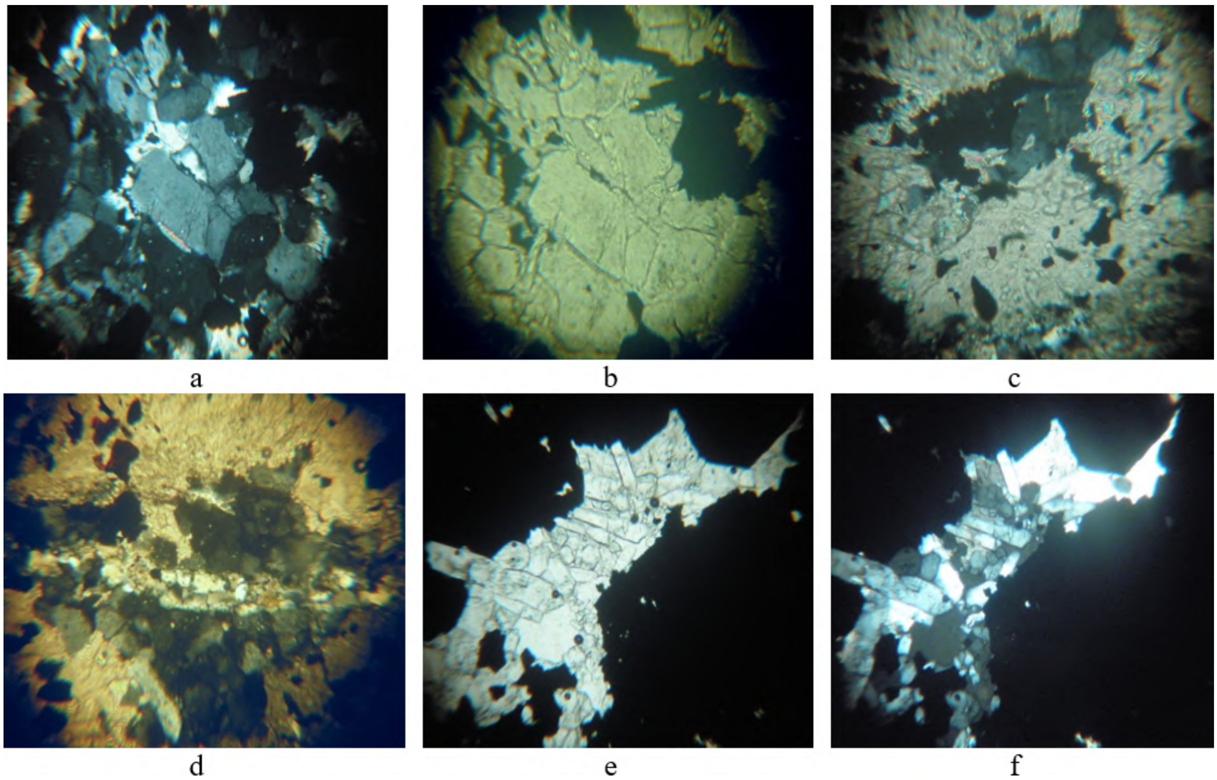

Figure 1. Iron ore raw materials in the light: a, b – nest-shaped aggregate of apatite; c – apatite in calcite mass; d – horizontally oriented quartz vein, apatite-calcite aggregate; e, f – apatite aggregate.

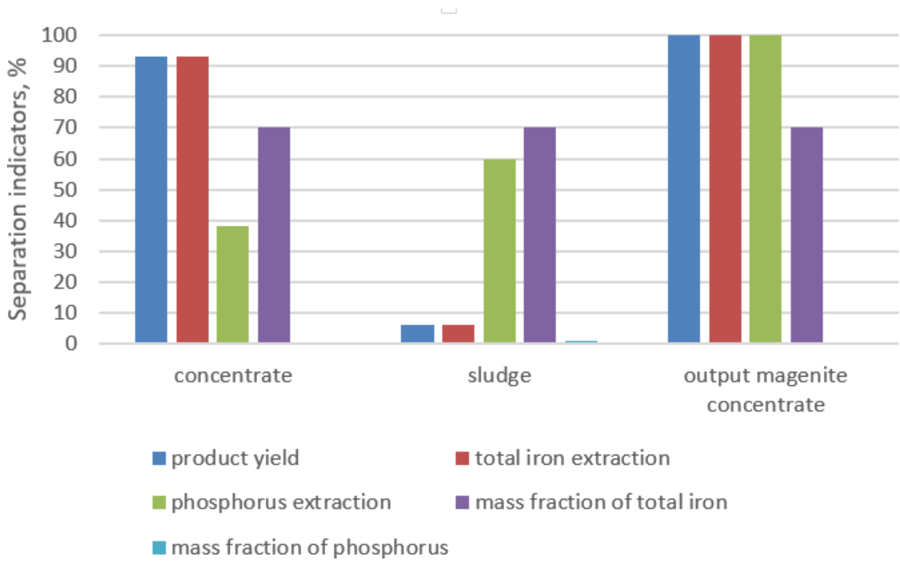

Figure 2. Indicators of magnetite concentrate de-sludging.

oxyhydryl collector during flotation studies. Saponified tallow oil is usually used in practice. DTOS is more selective compared to crude tall oil soap (CTOS). The main part of DTOS is salts (usually sodium) of inorganic fatty acids (oleic, linoleic, and linolenic), and the content of resin acids in it is no more than 10-15%. The increased content of resin acids (up to 30% or more) in CTOS makes it less suitable for obtaining high-quality concentrates due to the deterioration of its collector properties and increased foaming. The choice of such a collector was made, mainly, only empirically and based on the availability and economy of the reagent.

To establish the regularities of the flotation process, several experiments were conducted using the Latin square method, where the variables were the consumption of the regents – the collector, the depressor, the medium regulator, and the contact time with the reagents. The best indicators of dephosphorylation (according to the mass fraction of phosphorus in the concentrate) were obtained at the consumption of reagents (g/t): DTOS – 500 g/t, starch – 2500 g/t, soda – 1000 g/t.

It should be noted that during direct anionic flotation, a large part of hematite aggregates passes into the foam products, which leads to large losses of hematite with a foam product of 75-85%, which indicates the negative results of the conducted research.

Since the desired results were not achieved with direct anionic flotation of apatite, further studies were conducted on direct cationic flotation of apatite. In the study of direct cationic flotation of apatite, amines were used as collector reagents. Lilaflot reagent was used for flotation tests. These reagents are primary amines based on higher fatty acids with 17-21 carbon atoms in the radical. Lilaflot reagent is a mixture consisting of alkyloxypropylamine (60-80%) and alkyloxypropylamine acetate (20-40%). According to the parameters of high toxicity, the product can be classified as a moderately dangerous substance (hazard class 3). It should be noted that it decomposes completely into safe chemical compounds in the air within 24 hours

The use of cationic flotation is because, in comparison with anionic flotation, it does not require softening of water and large consumption of reagent. In addition, the duration of cationic flotation is 2-4 times shorter than that of anionic flotation.

The mechanism of action of amines consists in the hydrophobization of minerals during ion fixation, i.e. chemical interaction of ions and molecules of the collector, as well as their physical adsorption on the surface of the mineral, takes place. The reasons for the adsorption of a surface-active collector ion can be Coulomb attraction of the ion by the electrostatic field of the mineral surface, polarization of the adsorbent by the ion, electrostatic polarization of the ion by the surface field, and nonpolar Van der Waals forces. In turn, the adsorption of amine molecules, the polar group of which has a permanent dipole, depends on the possibility of dipole and dispersion interaction forces, the formation of a hydrogen bond.

A series of tests were conducted in laboratory conditions, which resulted in positive results: it was possible to reduce the mass fraction of phosphorus in the hematite concentrate by 2.87 times from 0.343 to 0.12%. The mass fraction of total iron in the hematite concentrate was 62.88%, which is 2.4% more than in the rough hematite concentrate.

In the third stage, the conditions of leaching of poor hydrogethite high phosphorus concentrate at high and low temperatures were investigated.

High concentration sulfuric acid was used in the research. The firing temperature was maintained at 800°C because at lower temperatures the process of destruction of the mineral structure is not carried out completely.

At a temperature of more than 1000°C, sintering of particles into agglomerates occurs, and access of the acid to the particles of the mineral, which contains phosphorus, deteriorates. As a result, the degree of phosphorus extraction decreases. Therefore, the optimal temperature is 900°C. This is the temperature at which the destruction of the structure of hydrogethite (FeOOH), recrystallization of iron, and displacement of phosphorus grains at the interface of phases (crystals) occurs. At the same time, artificial hematite $2FeOOH \rightarrow Fe_2O_3 + H_2O$ and phosphorus compounds are formed. Thus, access of mineral acid to phosphorus compounds and their transfer into solution is ensured. The firing time is 1 hour. This ensures a high level of phosphorus extraction into the solution during leaching. More time for firing is not required, because it also leads to the sintering of particles into agglomerates.

A weight of iron ore concentrate weighing 100 g was fired in a muffle furnace at a temperature of 900ºC for 1 hour. The cucumber was cooled to a temperature of 25ºC. Leaching was carried out with sulfuric acid with a concentration of 49% for 1 hour. The ratio of the solid to liquid phase was S÷L = 1÷1.5. The suspension was stirred, and after leaching it was filtered. The sediment on the filter was washed with a volume of 50 cm^3 of cold water. The sediment from the filter was dried at a temperature of 105ºC in a drying cabinet for 6 hours to a constant mass, and the content of phosphorus and iron was determined. As a result, a concentrate with a mass fraction of total iron of 55.2% and 1.2% phosphorus was obtained from a concentrate with a mass fraction of total iron of 56.4% and phosphorus – 0.15%.

5. Conclusions

1. The research was conducted on a sample of magnetite-hematite ore with the production of magnetite and hematite concentrate, which have a high mass fraction of phosphorus. As a result of the mineralogical study of the magnetite and hematite concentrate, it was established that the main carrier of phosphorus in the concentrates is apatite, which is found in fine fractions less than 20 μm.
2. To extract phosphorus from magnetite concentrates, it is sufficient to use de-sludging operations in the enrichment technology of rich magnetite-hematite ores, which can remove up to 61% of phosphorus.
3. For effective dephosphorization of hematite concentrates, it is necessary to use direct cationic flotation of apatite, with the help of which it is possible to remove more than 74% of phosphorus from the concentrate.
4. As a result of the analysis of the conducted research and the synthesis of the obtained scientific results, a technology for removing phosphorus from magnetite and hematite concentrates was developed, which allows reducing the mass fraction of phosphorus in the total concentrate from 0.14 to 0.04%.
5. With further improvement of the regime of flotation of hematite concentrates, it is planned to reduce the mass fraction of phosphorus to 0.02%.
6. The proposed technology of leaching of samples of poor hydrogethite high-phosphorus concentrates at high and low temperatures allows us to state that the parameters of the firing process allow the recrystallization of iron and therefore contribute to the access of mineral acid to particles containing phosphorus.

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The influence of deformation degree on efficiency of thin sheet cold rolling

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The influence of deformation degree on efficiency of thin sheet cold rolling

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Abstract. The objective of this research is to improve the efficiency of cold rolling of thin steel sheets with a thickness of 1.5 mm by determining efficient deformation degree. Low-carbon steel 20 was used for the research, and reduction patterns under conditions of cold rolling were determined. While maintaining a constant final sheet thickness of 1.5 mm, the deformation degree was observed to vary based on the initial thickness of the semi-finished rolled product. Key parameters, such as the initial temperature and rolling speed, were adjusted at 200°C and 1 m/s, respectively. The strip width was maintained as a constant, and a friction coefficient of 0.01 was adopted. The research delved into the deformation zone formed during longitudinal sheet rolling, defining its coefficients and essential parameters. Additionally, factors influencing the quality of the resulting sheet were identified. The research also explored the influence of the deformation degree on metal stress during the cold rolling process of thin sheets. This involved an analysis of yield strength, metal flow, and overall strength. Furthermore, the study established the rolling force and its variations with changing deformation degrees. An integral aspect of the study was the examination of the impact of the deformation degree on the process productivity of cold-rolled thin sheets. Through comprehensive analysis, a rational deformation degree was pinpointed, ensuring the production of a high-quality product with efficient strength and plasticity. This optimized degree also minimizes the required deformation forces and rolling torques, contributing to maximum process productivity.

1. Introduction

Within the metallurgical industry, considerable emphasis is directed towards the process of rolling production, a process by which sheet products are produced using cold rolling methods. Thin sheet products are used to create a big variety of lightweight welded and pressed structures, extensively contribute to mechanical engineering, aircraft manufacturing, and construction of manufacturing roofs, automotive components, airplane parts and bodies, household appliances, devices, as well as to food and chemical industries, among others. The application of such rolled products extends to the production of roll-formed sections, thereby facilitating a reduction in manufacturing costs. Requirements for thin-sheet rolling include specific criteria associated with wear resistance, strength, operational reliability, material hardness, pressability, and weldability; as well as dimensional accuracy, surface burriness, corrugation, and buckle, among other factors. These properties undergo notable transformations during the course of cold rolling, depending on the selected rolling patterns. To improve the quality of the final product, it is neccessary to develop ways for modifying material strength and hardness by adjusting rolling parameters. The obtaining of a high-quality and reliable product with minimized costs, maximized productivity and reduced power consumption, is achievable using advanced cold metal rolling technologies that shall be seleced based on the extent of metal deformation. Consequently, the research of the influence of deformation degree during the cold rolling of thin sheets on the parameters of process efficiency represents a relevant task. The resolution of this task will contribute to the identification of rational rolling patterns required for the production of high-quality products.

2. Analysis of literature data and problem defnition

Within the framework of the sustainable development program of metallurgical production, scientists from the Department of Ferrous Metallurgy and Foundry at Kryvyi Rih National University address the challenges of improving the quality of industrial products [1], where many issues are related to obtaining high-quality products. Rolling is the final stage of the entire metallurgical production, allowing the production of items due to the capability of metals and their alloys to undergo plastic deformation [2–6]. Hot rolling is applied for large-sized, low deformable products [3, 7, 8], while cold rolling is specifically used for small, highly deformable, and thin sheet products [3, 7–11].

The rolling process applied to sheet material represents a complex and cost-intensive technological proccess consisting of numerous operations with significant resource consumption [11, 12]. Thin sheet, defined as a product with a thickness below 4 mm, manufactured through cold rolling involving specialized operations, equipment, and tools. Within rolling mills, the cold processing technology facilitates the production of sheets with thickness ranging from 0.15 to 1.8 mm and width from 700 to 2300 mm, as well as tin sheets and strips with a thickness of 0.0015 mm. The initial material for cold rolling is hot-rolled sheets, predominantly composed of carbon or alloyed steel with a thickness of 1.6-6 mm [11, 12]. Thin sheets typically serve crucial purposes, finding applications in construction of roofing, and in the manufacturing of essential components and details for devices, automobiles, and aircraft. The physical and mechanical characteristics of thin sheets are subject to specific requirements, encompassing the following properties such as hardness, strength, elasticity, plasticity, reliability, stability, load-bearing capacity without fracture or cracking, and pressability etc., which are influenced by the metal's internal structure [13–15]. Additionally, standards concerning dimensional accuracy, surface burriness, corrugation, and buckle (properties determined by the rolling technology) are applied to thin sheets. Cold rolling significantly affects the mechanical, physical, and chemical properties of the rolled material, which can undergo substantial changes during rolling [15, 16].

As the deformation degree increases, the yield strength, proportionality limit, material plasticity, and electrical resistance increase. Moreover, it results in the increase of the material's strength and hardness, accompanied by a reduction in material density, plastic deformation capacity, elongation during the rolling process, thermal conductivity, and impact strength [17]. The collective occurrence of these phenomena is referred to as material strengthening or hardening, which complicates further material rolling.

During the rolling process, a complex deformation zone is established, wherein the primary transformation processes of the metal occur. Deformation zone is referred to as the volume of the metal alloy undergoing plastic deformation at a given moment [14]. A complex stressed state, requiring a substantial amount of power [18] is formed in the deformation zone during cold rolling. Literature recourses extensively describe the forces arising in the deformation zone [15–18] and the stability of the longitudinal rolling process of sheets. Additionally, considerable attention is given to the modeling processes during sheet rolling [19–21]. In the study [22], a meticulous analysis was conducted on the power consumption associated with temper rolling of thin sheets. Research on the power parameters of the cold rolling process of thin sheets was performed using the computer program DEFORM 3D [23]. This research determined the maximum forces and rolling torques generated during the rolling process. The manufacturing cost of the cold rolling

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process depends on the efficiency of the process, influenced by the following factors: material hardness and strength, power consumption, quality of the surface layer, equipment productivity, and the intensity of metallurgical equipment wear-out. To ensure high process efficiency, it is crucial to determine the deformation degree that allows achieving maximum process productivity while simultaneously obtaining products with efficient strength and hardness. This shall be done without subjecting the sheet material to plastic deformation during operation, preventing the formation of cracks and microfibers in the metallic alloy.

3. Purpose and tasks of research

Examine the impact of metal deformation degree during the cold rolling on its efficiency, ensuring the achievement of qualitative properties of material in the production of thin sheets with a thickness of 1.5 mm. To accomplish this objective, the following tasks shall be undertaken: investigate the influence deformation degree on the strength and stress characteristics of the material; determine the impact of deformation degree on amount of forces required for the process and on the rolling efficiency for obtaining cold-rolled thin sheets with a thickness of 1.5 mm; determine the efficient deformation degree.

4. Methodology of research

Low-carbon steel – grade 20 was used in the research to manufacture thin sheets with a thickness of 1.5 mm and a width (b) of 1000 mm during cold rolling. The initial rolling speed was 1 m/s, and a friction coefficient of 0.01 was adopted. Hot-rolled strips of variable thickness (ranging from 5 to 7 mm) were used as the initial material, introducing varying deformation degrees. Four experimental rolling patterns involving modifications of the initial stripe and deformation degree were developed for the research. The rolling forces were determined based on the results of prior research, as referenced in the literature source [23].

In the production of a thin sheet from a hot-rolled strip, it is required to determine the efficient reduction patterns that guarantee precise dimensions while minimizing manufacturing cost. During the execution of the research, the deformation zone (figure 1) formed during rolling process was thoroughly analyzed, and its coefficients and parameters were examined. This allowed to identify number of changes in the physical and chemical properties of the material during cold rolling.

In the research, the deformation degree (ε) was determined by the following formula:

$$\varepsilon = \frac{\Delta h}{h_0}, \tag{1}$$

where Δh is the absolute reduction calculated by the following formula:

$$\Delta h = h_0 - h_1. \tag{2}$$

The elongation of metal occurs during the rolling process, which is determined by the elongation coefficient (λ):

$$\lambda = \frac{F_0}{F_1} = \frac{L_0}{L_1}, \tag{3}$$

where F_0 is the cross-sectional area of the initial material; F_1 is the cross-sectional area of the finished product; L_1 is the sheet length after rolling, determined by the following formula:

$$L_1 = \lambda L_0, \tag{4}$$

L_0 was accepted as 10 m in the research.

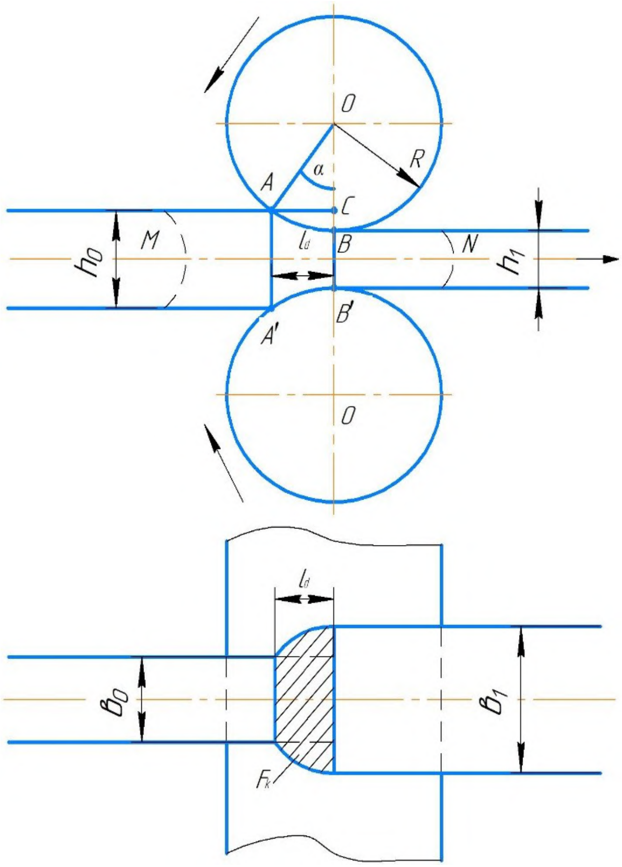

Figure 1. Strip deformation during rolling: $ABB'A'$ is deformation zone, h_0 and h_1 is sheet thickness before and after rolling, respectively, α is angle of strip bite during rolling, R is radius of the roll, F_k is contact area of the roll with the rolled material, l_d is length of the deformation zone, M is movement of metal entering the deformation zone, N is movement of metal exiting the deformation zone.

The theoretical calculation of the rolling force was performed using the formula [23]:

$$P = \sigma n_\sigma b l_d, \tag{5}$$

where σ is the material stress, measured in MPA; n_σ is the stress state coefficient, dependent on the rolling conditions and the size of the deformation zone [11]; b is the average strip width.

The average strip width was calculated using the formula:

$$b = \frac{b_0 + b_1}{2}, \tag{6}$$

where b_0 and b_1 are the strip width before and after rolling, respectively.

The length of the deformation zone depends on the absolute reduction value and the radius of the rolls, and it was determined by the formula:

$$l_d = \sqrt{\Delta h R}. \tag{7}$$

To determine the efficiency of thin sheet production, the process productivity per second was calculated using the following formula:

$$\Pi = \frac{m}{t}, \tag{8}$$

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where m is the sheet weight measured in kg; t is the rolling time measured in s.

The sheet weight depends on the product dimensions and material density, determined by the following formula:

$$m = l_1 h_1 b_1 g, \tag{9}$$

where g is the material density, which equals $g = 7867$ kg/m^3 for steel products.

The formula for determining the rolling time is the following:

$$t = \frac{L_0}{\upsilon_0}, \tag{10}$$

where υ_0 – initial rolling speed, measured in m/s.

For all cases, it was determined that the rolling time t equals t=10 s.

Changes in rolling forces (table 1) and process productivity (table 2) depending on the deformation degree were calculated using the initial data and the provided formulas. The efficiency of the cold rolling process was determined by the amount of forces and rolling torques for rolling, as well as the process productivity. The quality of the product was assessed based on material stress, yield strength, ductility, and material strength.

5. Results and their explanation

The research enabled to determine changes in the properties of cold-rolled steel. The impact of deformation degree during cold processing on stress is presented in figure 2, allowing the determination of the efficient reduction pattern.

As shown in figure 2, an increase in deformation degree leads to an increase of stress during cold rolling. At low deformation degrees (up to 30%), the material is incapable of plastic deformation, exhibiting elastic deformations. When deformation degree exceeds 40%, the material begins to undergo plastic deformation. With deformation degree surpassing 60%, the material starts to strengthen and gradually reaches the yield strength limit. In cases where the deformation degree exceeds 80%, rolling becomes impractical due to a high probability of crack formation in the solid material and subsequent product destruction. Using a sheet with such defects is impossible. These data shall be considered when developing a technological process to obtain a durable product.

The results of the influence of reduction patterns on material stress during cold rolling and the calculations of the changes of required power consumption for producing cold-rolled thin steel with a thickness of 1.5 mm are presented in table 1.

Table 1. Results of the research of force parameters of cold rolling*.

$Pattern, \#$	σ, MPa	b, mm	h_0, mm	h_1, mm	$\varepsilon, \%$	Δh	F_0, m^2	F_1, m^2	λ	L_0, m	P, MN	$\Delta P, \%$
1	740	1000	5	1.5	70	3.5	0.05	0.015	3.33	33.33	5,3	-
2	755	1000	6	1.5	75	4.5	0.06	0.015	4.0	40.0	6.15	+16
3	765	1000	7	1.5	78.6	5.5	0.07	0.015	4.67	46.67	6.8	+28
4	735	1000	4	1.5	62.5	2.5	0.04	0.015	2.67	26.67	4.4	-17

* σ – yield strength of the material; P – rolling force; ΔP – change in rolling force

The change in rolling force ΔP was determined by the following formula:

$$\Delta P = \frac{P_i - P_1}{P_1} 100\%, \tag{11}$$

where P_i is the rolling force of the respective pattern; i is the pattern number.

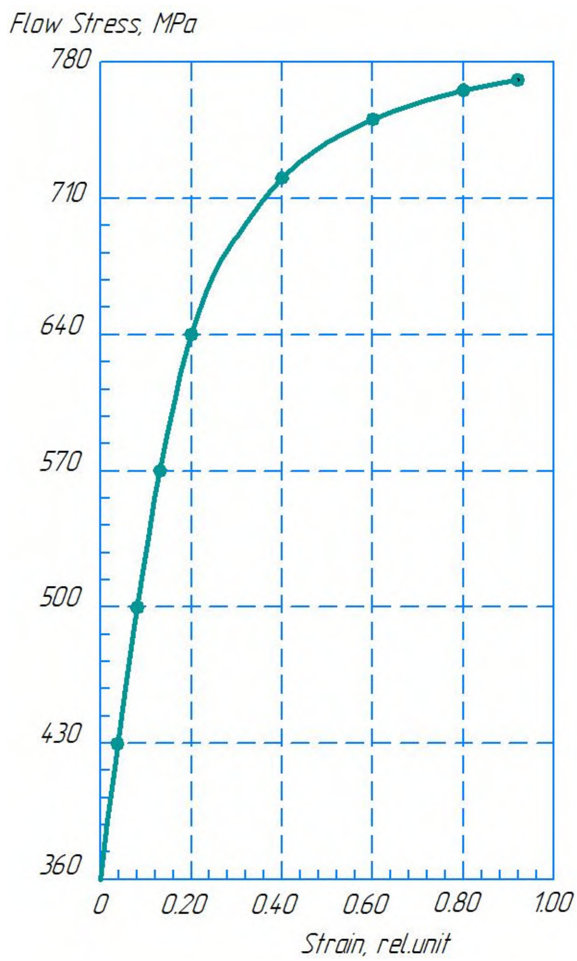

Figure 2. Stress-strain diagram.

The change in productivity $\Delta\Pi$ of the process was determined by the formula:

$$\Delta\Pi = \frac{\Delta\Pi_i - \Delta\Pi_1}{\Delta\Pi_1} 100\%, \tag{12}$$

where $\Delta\Pi_i$ is productivity of the respective pattern.

The strengthening of steel products is characterized by an increase in the hardness of surface layer. The influence of deformation degrees.during cold rolling on the metal strengthening is presented in figure 3.

The data in figure 3 clearly indicates that metal strengthening during cold processing occurs more intensively at lower deformation degrees. With a deformation degree exceeding 70%, the hardness reached its maximum for the given material and demonstrates negligible further changes. Subsequent reduction becomes complicated as steel loses its plastic properties and the capacity for plastic deformation. Therefore, additional reduction will lead to the sheet destruction. The research has shown that material density is also capable of changing during cold rolling (figure 4).

Figure 4 illustrates that the density of Grade 20 steel decreases with an increase of deformation degrees, leading to a decrease of the product mass. However, such a decrease is insignificant, providing a basis to ignore the density decrease in calculations.

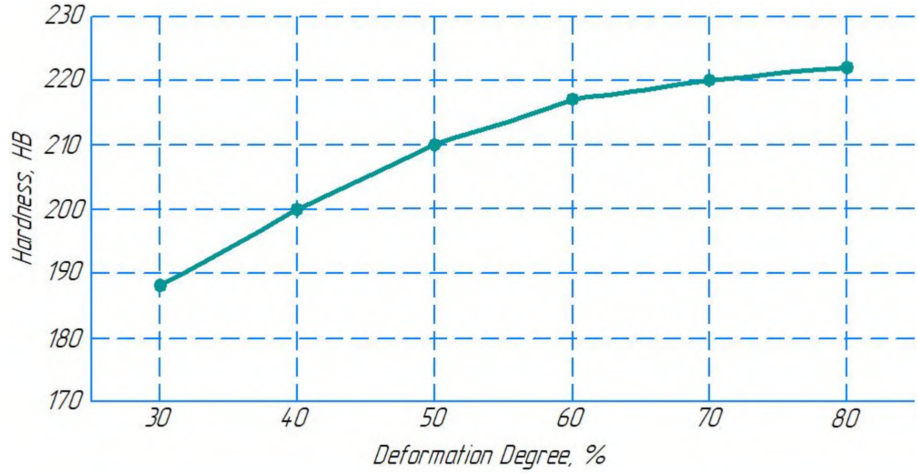

Figure 3. Influence of reduction value on material hardness for grade 20 steel.

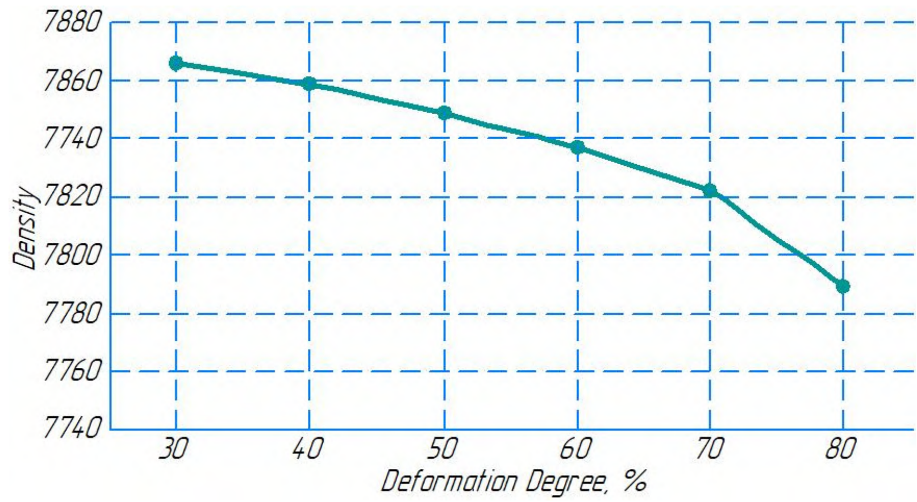

Figure 4. Influence of reduction degree on the density of grade 20 steel.

The results of the influence of the deformation degree on the change of productivity per second of the cold rolling process of thin sheets are presented in table 2.

Table 2. Results of the research on the influence of reduction patterns on the productivity per second of rolling process of thin sheets**.

$Pattern, \#$	$\varepsilon, \%$	m, kg	Π, kg/s	$\Delta\Pi$, %
1	70	3929	392.9	–
2	75	4715	471.5	+20
3	78.6	5501	550.1	+40
4	62.55	3144	314,4	-20

** $\Delta\Pi$, % – change of process productivity

Based on the research results, graphical dependencies were constructed to illustrate the influence of the deformation degree on the rolling force and process productivity (figure 5).

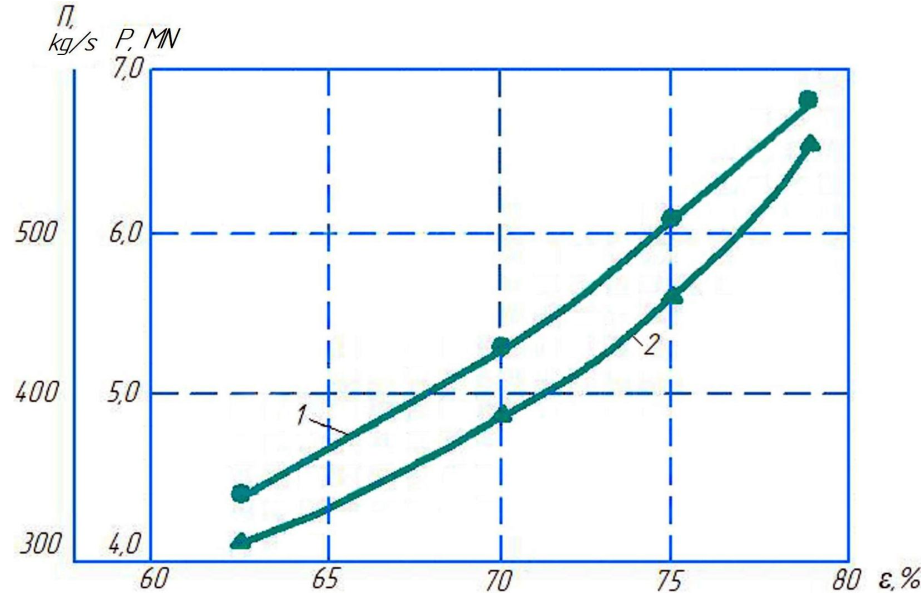

Figure 5. Influence of the deformation degree on the cold rolling force (curve 1) and process productivity (curve 2): P, MN is rolling force; П, kg/s is process productivity per second.

Figure 5 illustrates that an increase in deformation degree leads to an elevation in rolling force and process productivity. The increase of metal deformation force indicates that the cold rolling process of thin sheets becomes more challenging with the growth of deformation degrees. The rise in rolling force contributes to increased stress on the processing tool, leading to more intensive wear-out of the rolls. Additionally, there is an increase of power consumption during the process, resulting in an increase of the production cost of the obtained product, which is a disadvantage. The increase of process productivity indicates an increase in the quantity of manufactured sheets per second, presenting a positive aspect in the manufacturing of rolled products. Following a thorough analysis of the provided data, it has been determined that the most efficient pattern is cold rolling with a deformation degree of 70%. A 5% increase in the deformation degree proves advantageous, resulting in a 20% enhancement in process productivity. However, the rolling force also increases by 18%, leading to higher power consumption. Additionally, it is essential to take into consideration that material stress increases, potentially resulting excessive deformation resistance and the formation of cracks, microcracks, and other defects in the sheets. Furthermore, an increase of deformation degree may lead to elastic displacement of the rolls, negatively impacting the accuracy of dimensions and the quality of the sheet surface layer. When decreasing the deformation degree by 7.5%, a decrease in rolling force by 17% is observed, which is positive in terms of power consumption. However, rolling of the material under such conditions is accompanied by a 20% reduction in process productivity, which is a significant drawback. Moreover, under these conditions, the material does not achieve efficient strength and hardness, which can lead to plastic deformation of the sheet during its operation.

6. Conclusions

The process of manufacturing thin-sheet cold-rolled low-carbon steel 20 with a thickness of 1.5 mm has been studied, and the effect of the deformation degrees on the stress of steel 20, the strength characteristics of the material, the change in rolling force, and the productivity of the process have been determined. This allowed determining the technologically efficient deformation degree. It is reasonable to set the deformation degrees as 70%, ensuring quality indicators of cold rolling. Rise of the deformation degrees increases the productivity of the process, but at the same time, the material significantly strengthens, loses the ability to plastic deformation, making the rolling process impossible. Decreasing the deformation degrees does not allow achieving the required strength of the thin sheet and reduces the productivity of the process.

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Melamine-doped TiO_2 as a perspective photocatalyst for hydrogen evolution

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Abstract. The photocatalysts based on titanium dioxide (TiO_2) doped with melamine were synthesized. The samples of pure and modified TiO_2 were analyzed using X-ray diffraction (XRD) analysis, Brunauer-Emmett-Teller (BET) surface area analysis, and room temperature FT-IR, Raman, and UV-Vis diffuse reflectance spectroscopy. It was established that modifying TiO_2 with melamine leads to a decrease in the crystallite sizes and an increase in the lattice parameters and molecular unit volume. The stoichiometry of modified TiO_2 worsened due to the appearance of additional vacancies of oxygen in the doped samples. The photocatalytic activity of the prepared catalysts in the reaction of hydrogen production from water under light illumination was studied. The melamine-doped TiO_2 samples showed more than two times higher activity than pure titanium dioxide.

1. Introduction

Developing of highly efficient technologies for producing hydrogen from water is relevant and exciting. Hydrogen as a clean energy source has excellent prospects. Getting hydrogen from the photocatalytic decomposition of water under the action of UV and visible light is generally considered the most straightforward and cheapest technology for hydrogen production [1–3]. However, the main problem is finding the most efficient photocatalyst for this process. Among many photocatalysts, TiO_2 is the most efficient and promising [4–6]. TiO_2 is preferred due to its appropriate electronic properties, non-toxicity, chemical inertness, and low cost. Meanwhile, the TiO_2 disadvantage is that it absorbs only a tiny fraction of solar radiation (about 3–5 %). The UV absorption edge (and corresponding optical band gap Eg values) for different polymorphic phases of TiO_2 are somewhat different: about 387 nm ($Eg \sim 3.2$ eV) and 413 nm ($Eg \sim 3.0$ eV) for anatase and rutile, respectively. Many methods are used to increase the photocatalytic efficiency of TiO_2: introduction of metal (Fe, Co, Pt, Nb, Cu, etc.) [6–8] and non-metal (N, S, B, C) elements [9–11], etc.

It has been reported [12–17] that one of the promising ways to increase the photocatalytic activity of TiO_2 is its modification with melamine. Melamine $C_3H_6N_6$ has been shown to be a promising carbon and nitrogen source for the TiO_2 modification. It is known that melamine melts at 345°C with decomposition; when heated to 354°C and above, melamine off-gases ammonia with the formation of melem, which, at temperatures above 360°C, turns into cyanic (or isocyanic) acid. Judging by the literature data, in the high-temperature range of 530–555°C, graphitic carbon nitride g-C_3N_4 can be formed from melem. Recent studies have shown that g-C_3N_4 obtained at 550°C absorbs light in a wide spectral range and shows an increasing photoactivity [18]. However, XPS analysis showed the absence of nitrogen in our samples. Obviously, during the heat treatment of the samples, nitrogen was degassed as ammonium.

Therefore, our work aimed to obtain and characterize melamine-modified TiO_2-based photocatalysts with a further study of photocatalytic activity in the reaction of hydrogen generation from water using solar energy.

2. Experimental methodology

2.1. Samples preparation

The TiO_2 powders were synthesized by the sol-gel method. For the undoped TiO_2 preparation, the titanium(IV)butoxide ($C_{16}H_{36}O_4Ti \geqslant 99.9$ %, Aldrich), citric acid ($C_6H_8O_7$), and glycerol ($C_6H_8O_3$) were mixed to obtain uniform mass at room temperature and further calcinated at 500°C for two hours in the presence of air oxygen. The samples of melamine-doped TiO_2 were obtained using the same mixture but with the additions of melamine (4 and 8 %) before the heat treatment.

After cooling, the powders were triturated until smooth. The 4- and 8-wt.% melamine-doped TiO_2 samples were labeled as 1M/TiO_2 and 2M/TiO_2, respectively. The powder's color ranged from yellow to brown.

2.2. Instruments and methods

The XRD patterns of TiO_2 samples were obtained using a Bruker D8 Advance X-ray diffractometer with monochromatic $Cu_{K\alpha}$ – radiation ($\lambda = 0.154$ nm). The average crystallite size of the TiO_2 samples was evaluated from the A (101) characteristic peaks broadening using the Debye-Scherrer formula: $D = K\lambda/\beta\cos\theta$ where D is an average crystallite size in Angstroms, K is a constant equal to 0.89; λ is the X-ray radiation wavelength, β is the diffraction peak full width at half maximum (FWHM), and θ is a diffraction angle. The measurement errors for the XRD did not exceed ±5 %.

The FT-Raman spectra of the prepared TiO_2 powders were recorded in 80–4000 cm^{-1} spectral range using a Bruker IFS-88 Fourier spectrometer equipped with FRA-106 attachment (Nd:YAG laser, λex=1.064 μm, power 300 mW, backscattering geometry, spectral resolution 2 cm^{-1} and 128 scans accumulated for each spectrum).

The room temperature FT-IR spectra were recorded with a Perkin Elmer Spectrum One spectrometer in the spectral region of 4000-400 cm^{-1} with a spectral resolution of 4 cm^{-1}. For the FT-IR transmission spectra measurements, the samples were ground with KBr powder in a weight ratio of 1:200 and pressed into transparent KBr discs.

The prepared powders UV-Vis diffuse reflectance spectra (DRS) were measured using a Perkin-Elmer Lambda Bio 35 spectrophotometer in the 200–1000 nm wavelength range. The Eg value was estimated by extrapolating the linear part of the graph $(h\nu \cdot \alpha(h\nu))1/n$ vs $h\nu$ towards the energy axis at $\alpha(h\nu) = 0$, where $n = 1/2$ for direct allowed transitions, $n = 2$ for indirect allowed transitions.

The prepared catalysts specific surface area (S_{BET}) and pore size distribution were determined using a Quantachrom Nova Win 2 device. The specific surface area of the samples was determined based on nitrogen adsorption-desorption isotherms using the Brunauer–Emmet–Teller (BET) approach.

Photocatalytic hydrogen evolution was studied in a cylindrical glass temperature-controlled reactor. In the experiment, the prepared photocatalyst (0.03 g) was dispersed in 10.0 ml of an aqueous solution containing 2 mol/l of ethanol (electron donor). The Pd/SiO_2 co-catalyst (0.01 g) was obtained by the reduction of $PdCl_2$ with hydrogen on the surface of commercial silica (1 wt% palladium on SiO_2) and was added into the mixture [19].

The reaction mixture was degassed before the light irradiation using a vacuum pump. The suspension was irradiated using a high-pressure mercury lamp (DRSH 1000; 1000 W; $\lambda_{\max} = 365$ nm; 50 mW/cm^2) under constant stirring with a magnetic stirrer. The gas phase composition above the solution was evaluated chromatographically every 30 min.

3. Results and discussion

The XRD patterns of the undoped and melamine-doped TiO_2 samples show the diffraction peaks at $2\theta = 25.6$; 37.8; 48.1; 54.1; 55.0; 62.9; 69.2; 75.1 corresponding to anatase, and one small peak at $2\theta = 27.4$ that corresponds to the rutile crystal structure (figure 1). The rutile content did not exceed ∼12 % wt.

The overall XRD intensity from M/TiO_2 powders decreases compared with that from undoped TiO_2. Such a decrease may occur due to the TiO_2 lattice deformation or reduction of crystallite size after the modification. Indeed, from the XRD data analysis, the TiO_2 modification with melamine leads to a decrease in the crystallite sizes and some changes in the lattice parameters (table 1).

Table 1. Phase composition and structural characteristics of the prepared photocatalysts.

Sample	Interplanar spacing, d, nm	Lattice parameters, Å	Crystallite size, D_{hkl}, nm	Volume molecular unit TiO_2, V=a^{2}c, Å^3	Axial ratio, c/a
TiO_2	0.348	a = 3.7774 c = 9.2030	10.2	131.32	2.44
$1M/TiO_2$	0.348	a = 3.7894 c = 9.4590	7.6	135.83	2.49
$2M/TiO_2$	0.349	a = 3.7847 c = 9.4681	9.2	135.62	2.5

Modification led to the increasing of lattice parameters and molecular unit volume of TiO_2 and prevent the growth of crystallites during the heat treatment (table 1).

Besides that, the observed increase of the lattice parameters can occur due to the formation of more stoichiometric phase of TiO_2. We used FT-Raman spectroscopy to determine the stoichiometry and the sizes of nanocrystallites in the prepared TiO_2 catalysts (figure 2, table 2, table 3).

It was reported that the positions ($\nu_{\max}$) of the low-frequency phonon mode of TiO_2 crystal lattice Eg=144 cm^{-1} (for anatase) and its half-width ($\Delta\nu_{1/2}$) are very sensitive to the stoichiometric ratio (O/Ti), as well as to the size of TiO_2 nanocrystallites [22].

Based on the $\nu_{\max}$ vs O/Ti and ($\Delta\nu_{1/2}$) vs O/Ti correlation plots [22] it has been found that when TiO_2 samples are doped with melamine, their stoichiometry O/Ti ratio is getting worse (table 3). This is due to the appearance of additional oxygen vacancies in the doped samples. When oxygen vacancies appear in TiO_2, the oxygen environment of the titanium atoms and their valence state undergo changes, and the transition of the titanium atoms from one valence state to another takes place. The presence of oxygen vacancies in the electronic band structure of TiO_2 is associated with Ti^{3+} cations. With the appearance of the oxygen vacancies, the

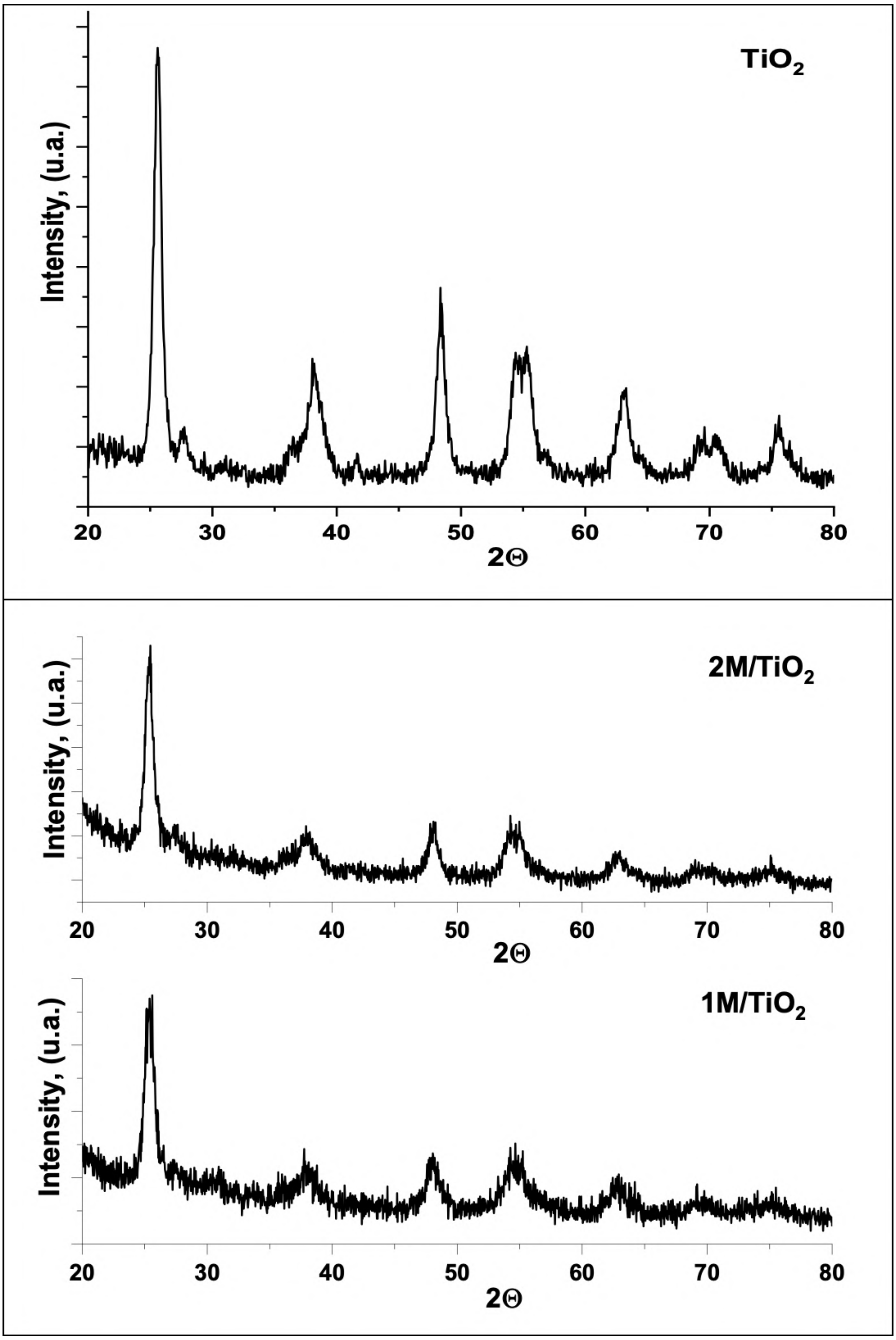

Figure 1. XRD patterns of undoped and melamine-doped TiO_2.

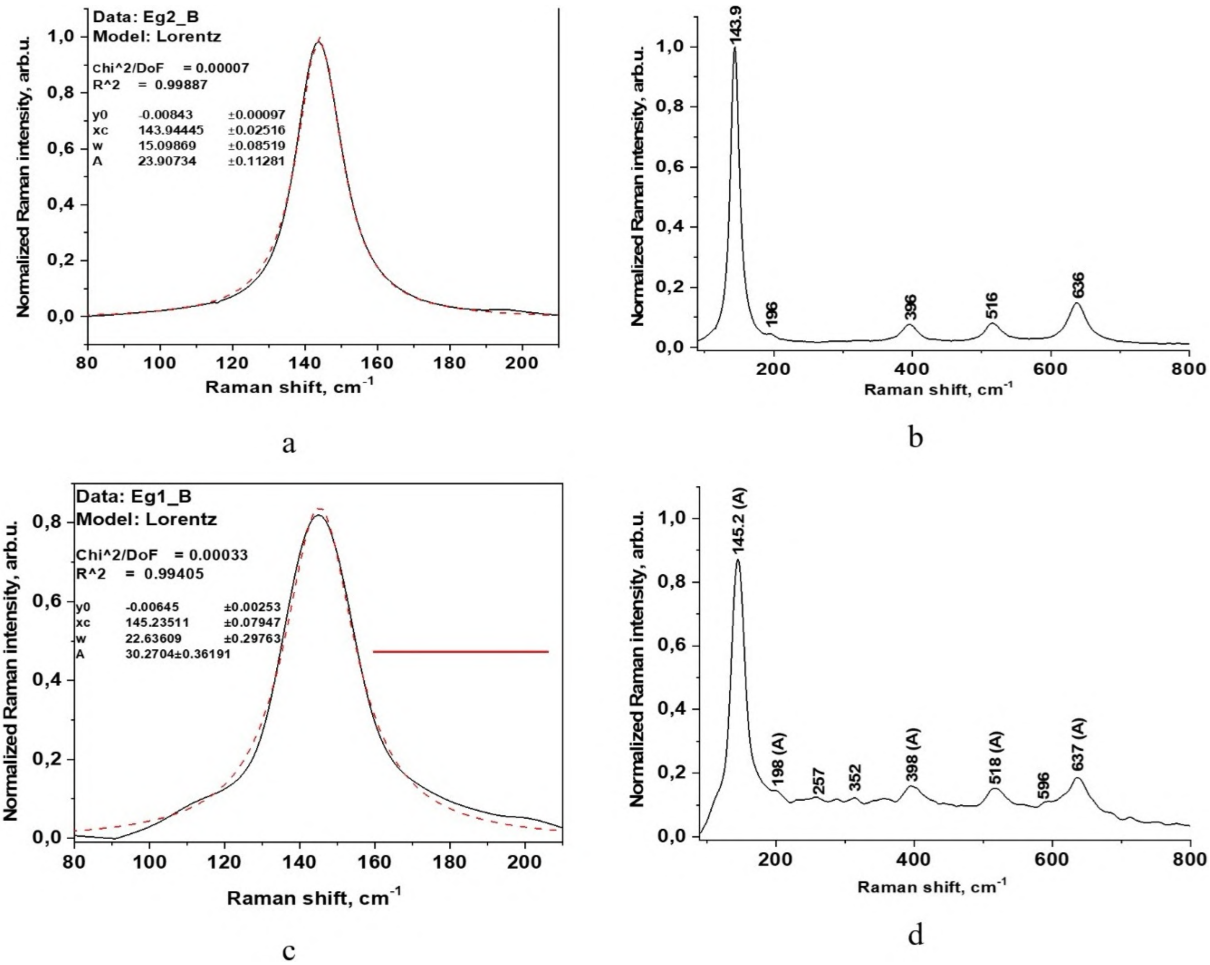

Figure 2. FT-Raman spectra of the prepared photocatalysts: a, b – TiO_2 and c, d – $2M/TiO_2$.

Table 2. Raman-active phonon modes of anatase TiO_2 and $2M/TiO_2$ samples.

Raman shift, (cm^{-1}), Anatase TiO_2	Raman shift, (cm^{-1}), $2M/TiO_2$	Assignment	Literature data, (cm^{-1})
143.9	145.2	*Eg*	153 [20], 147 [21]
196	198	*Eg*	201 [20], 198 [21]
396	398	Blg	402 [20], 400 [21]
516	518	Alg, Blg	522 [20], 515 [21]
636	637	*Eg*	643 [20], 640 [21]

local electrostatic balance is disturbed, and the transition of titanium atoms from one valence state to another occurs ($Ti^{4+} + e^- \rightarrow Ti^{3+}$). The changes in the oxygen content may be also accompanied by structural transformations. In addition, corresponding decrease in the size of TiO_2 nanocrystallites is observed.

The FT-IR absorption spectra of the TiO_2, $1M/TiO_2$ and $2M/TiO_2$ photocatalysts show the bands around 500–700 cm^{-1} (Ti–O–Ti), 900 cm^{-1} (Ti–O) [23], 1300-1600 cm^{-1} (C-O stretching and OH bending), 2343 cm^{-1}1 (physically adsorbed carbon dioxide [24]) and strong wide band

Table 3. Stoichiometric ratio, the nanocrystallite sizes and S_{BET} for the pure anatase and $2M/TiO_2$ samples.

Samples	Stoichiometric ratio, O/Ti	Sizes of TiO_2 nanocrystallites, nm	S_{BET} m^2/g
TiO_2	1.993-1.995	12-23	54
$2M/TiO_2$	1.983-1.990	7-13	68

at 3200 cm^{-1} (absorption of OH stretching vibrations corresponding to stretching vibrations of Ti–OH groups involved in a weak hydrogen bond (~5 kcal/mol [25] with physiosorbed water molecules). Modified samples have additional bands at 2840–2893 cm^{-1} originating from stretching vibrations of the C–H and $–CH_2$ bonds).

The UV–vis absorption spectra of the prepared catalysts were measured to determine the band gap values of M/TiO_2 and un-doped TiO_2. The value of the band gap (Eg) was estimated from the dependence $(\alpha hv)^2 = f(hv)$ by extrapolating the linear region of the spectrum to the intersection with the abscissa axis, i.e., at $(\alpha hv) = 0$ (figure 3). It was revealed that the band gap value of the prepared catalysts changes from 3.27 eV (TiO_2) to 3.14 eV ($1M/TiO_2$) and 3.32 eV ($2M/TiO_2$).

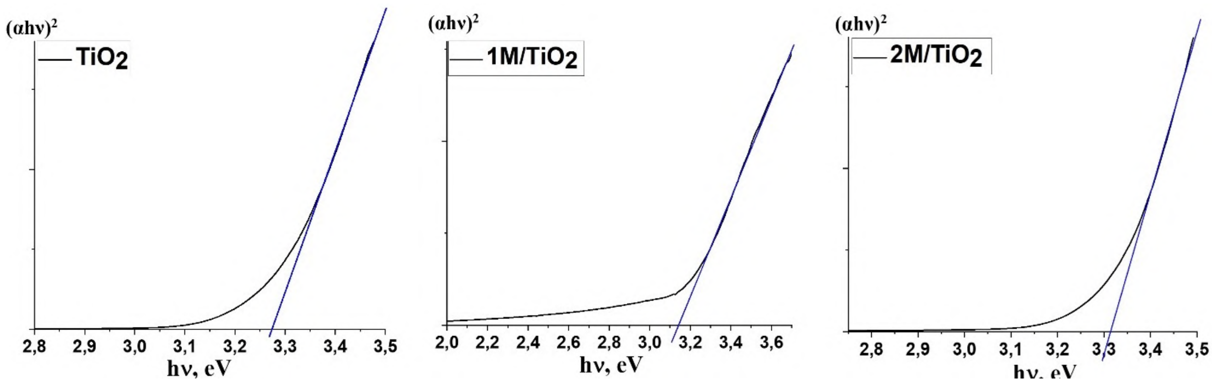

Figure 3. Plots of $(\alpha hv)^2$ versus photon energy ($f(hv)$) of the prepared catalysts.

We investigated the water splitting reaction in the presence of TiO_2 and M/TiO_2 photocatalysts under the light illumination with a power density of 50 mW/cm^2 from a high-pressure mercury lamp. The photocatalytic decomposition of water into hydrogen and oxygen requires the presence of a photocatalyst, an electronically excited semiconductor with a band gap less than the energy of the incident light ($hv > Eg$) [26].

As we have found, the melamine-modified TiO_2 catalysts ($1M/TiO_2$) showed more than two times higher activity (figure 4) than undoped TiO_2.

The $1M/TiO_2$ catalysts appeared to be the most photocatalytically active. Firstly, due to the decrease in the particle size, the rate of volumetric recombination of photoinduced charge carriers also decreased significantly – they reached the surface much faster than the average time of volume recombination. The second reason is the narrowing of the band gap.

4. Conclusions

A set of photocatalysts based on titanium dioxide doped with melamine were successfully synthesized to obtain the highly effective photocatalyst for hydrogen generation. It has been

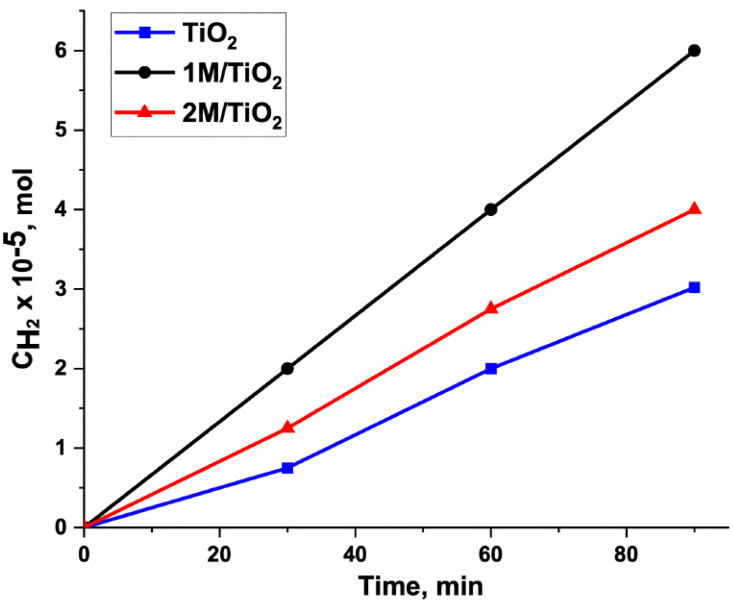

Figure 4. Kinetic curves of the photocatalytic hydrogen evolution from aqueous/ethanol solution.

found that TiO_2 modification with melamine decreases crystallite sizes and changes in the lattice parameters of TiO_2. The stoichiometry of modified samples deteriorates indicating the existence of additional oxygen vacancies in the doped samples. Changes in the oxygen content may be accompanied by the appearance of Ti^{3+} energy levels in the forbidden band of TiO_2.

The enhanced photocatalytic activity of $1M/TiO_2$ towards hydrogen production in the reaction of water splitting, which appeared to be more than twofold higher compared to unmodified TiO_2, is mainly attributed to the narrowing of the band gap, an increased number of surface active sites, and a decrease of photo induced charge carriers recombination rate due to the decreased particle size. This study suggests that the proposed simple way for TiO_2 modification with melamine can be used to obtain new M/TiO_2 materials with improved activity on hydrogen production and industrial wastewater treatment under the action of UV and visible light for creation of green energy and clean environment.

Declaration of interests

The authors claim that they don't have competing financial or personal profits that could have appeared to affect the work.

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Effect of the electrochemical impact on copper-molybdenum flotation separation

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Abstract. Lime is used in the classical copper-molybdenum-pyrite flotation for pyrite depression. Often copper-molybdenum flotation separation is conducted with nitrogen and copper minerals are depressed with the aid of phosphorus- or sulfide-based compounds. The mentioned methods are relatively expensive, difficult for handling, sometimes desired results are not achieved and valuable metals are lost. An electrochemical depression of pyrite, followed by an electrochemical depression of copper minerals is suggested and aimed at increasing the recovery of metals and improving the processes' control. The impact is achieved both by electrodes immersed in the flotation pulp or by using preliminary produced catholyte for pulp preparation. Effective copper-pyrite and copper-molybdenum flotation separation can be achieved under air conditions at significantly reduced amounts of reagents used, latter leading to improved environmental impact.

1. Introduction and brief theoretical basis of copper-molybdenum flotation separation

The present-day industrial technology increasingly needs materials that are operative under high stress, extended temperature ranges, and extremely corrosive environments. Molybdenum (Mo) is used as an alloying component in steel, cast iron, and super-alloys to harden them and enhance their toughness, strength, corrosion and wear resistance. Furthermore, molybdenum is used as a refractory metal in many chemical applications, such as catalysts, lubricants, and pigments. Molybdenum is expected to become an increasingly important factor in environmental protection technology by its use in high-strength steels for automobiles in order to reduce weight at increased safety and advance fuel economy. With the aim to fulfill the requirements for reducing the carbon dioxide emissions from coal-fired power stations, the industry will built plants running at higher temperatures, which will result in greater demand for higher grade molybdenum-bearing steels. Few of molybdenum's uses have acceptable substitutes. Increase in molybdenum use in stainless and specials steels is expected to continue. For example, the estimated apparent consumption in 2022 increased by 96% compared with that in 2021 and the trend is expected to continue [1, 2].

Large part of the molybdenum concentrate production comes as a byproduct from copper-molybdenum (Cu-Mo) sulfide ores [2, 3]. Porphyry copper deposits are among the most important resources of copper and molybdenum. In these ores chalcopyrite and pyrite are most often the dominant minerals and the molybdenite (molybdenum disulfide, MoS_2) is the main molybdenum mineral [4, 5].

Although some oxidation methods have been studied to selectively recover and separate chalcopyrite and molybdenite [6–9], they have not found large industrial application.

In the most widely used flotation flow sheets of these ores in the first stage bulk copper sulfide concentrate, containing molybdenite, is obtained. In the second flotation stage molybdenum and copper concentrates are separated [3, 10, 11] (figure 1).

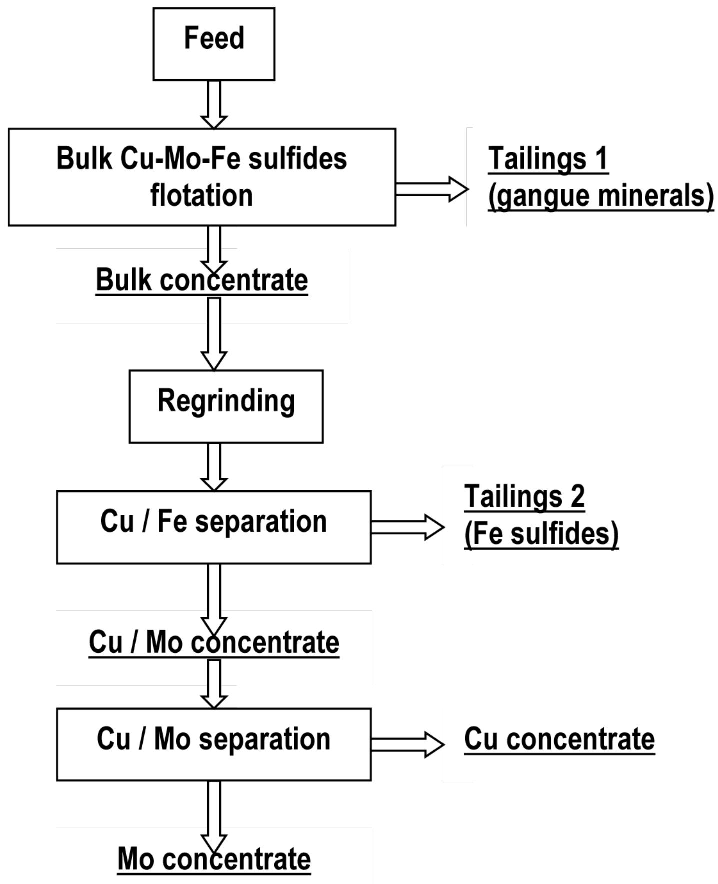

Figure 1. Schematic typical general flow sheet for recovering Cu and Mo from porphyry Cu–Mo ores-adapted from [10].

Usually an alkaline pulp (pH 8.5 - 11) is maintained (most often by lime addition 1 – 4 kg/t), in order to produce a stable froth with good carrying power (when xanthate or/and dithiophosphate collectors are used). A lower pH (i.e. 8.5 – 9.5) is more desirable in the case of chalcopyrite ore, since at a higher pH, the floatability of chalcopyrite is reduced, while chalcosine flotation needs pH > 11.5, [12].

Lime addition also results in pyrite depression in the first stage. Generally, depression of pyrite in the case of porphyry ores, containing chalcopyrite, is at pH about 10.5–11 [12]. Both chalcopyrite and molybdenite are well floating (recovery $> 90\%$) in the pH range 7-10 [13–15].

In the second stage depressants are added in order to decrease the effect of the residual collectors left in the bulk concentrate and to depress (generally, by destroying the copper collector) the flotation of copper sulfides, such as chalcopyrite. Different depressants are used, such as sulfur-containing compounds-sodium sulfide Na_2S, sodium hydrosulfide $NaHS$, Nokes reagent ($P_2S_5 + NaOH$), Na_2SO_3, and $Na_2S_2O_3$ [10, 16]. This method is the most commonly used and involves concentrate dewatering before conditioning with the depressant [12]. Nitrogen-containing compounds ($NaCN$, $Na_4[Fe(CN)_6]$, $Na_3[Fe(CN)_6]$, $NaCN$, KCN, $Zn(CN)_2$, $Ca(CN)_2$, etc.) are the other type of applied Cu depressant [17]. Generally, the depressants are created to react with the uncovered copper and iron ions on chalcopyrite surface and theoretically, the floatability of molybdenite is virtually unaffected, due to the absence of reaction sites [3]. Although the use of inorganic depressants such as $NaHS$ and $NaCN$ effectively depresses copper sulfides and separates Cu and Mo minerals, these reagents have some disadvantages, such as potential release of toxic gases (H_2S and HCN) when pH is out of control, inadequate molybdenite recovery, a possible loss of gold and silver contained in some ores when $NaCN$ is used, and corrosion of storage tanks and pipes [15–17]. Therefore, different organic depressants are studied as eco-friendly and inexpensive reagents [13, 18–20]. Mono- or poly-nuclear complexes are formed by donor atoms (such as nitrogen, sulfur and oxygen) in these compounds with transition metal ions (i.e. Cu and Fe) on chalcopyrite thus depressing it [10]. However, some of these chemicals can cause health problems at working places (such as eye irritation, respiratory irritation, skin irritation [21–23]. Trithiocarbonate may decompose to carbon disulfide that besides above described negative effects causes reproductive toxicity, coronary heart disease, retinal angiopathy, effects on peripheral nerves, psycho-physiological effects, etc [24].

While Cu-minerals are depressed, molybdenite is recovered as a flotation concentrate by using petroleum-based collector and alcohol frothers. Molybdenum oxide is produced by the molybdenite concentrate roasting or acid pressure-oxidation processes [10].

It is established that in plant practice, the correct selection of modifier, frother, collector and operating parameters (i.e. pulp density, mineral particles size, pH, oxidation-reduction potential) ensures an efficient process [12, 25, 26].

When porphyry copper and copper–molybdenum ores are processed the reagent schemes in bulk Cu-Mo concentrate producing stage are relatively simple and usually involve lime as a modifier, xanthate as collector for Cu ores and fuel oil or kerosene – for molybdenite, and frother (most often pine oil, methyl isobutyl carbinol or glycols). However, the lime used as pH modifier, may depress a portion of the molybdenum, causing a decrease in the obtainable recovery of MoS_2 mineral [4, 10, 27, 28].

The reagent scheme used in copper–molybdenum separation stage depends on the type of copper minerals present, type of reagent scheme used in the previous stage and the presence of other impurities in the concentrate. When chalcopyrite is the main Cu mineral or Cu is presented as a mixture of chalcopyrite and bornite, either $NaHS$ or Na_2S is used as depressant in the copper–molybdenum separation [12].

It is considered that $Cu(I)$-xanthate (CuX), formed by reaction (1) is needed for initial flotation of chalcopyrite and adsorbed dixanthogen (X_2), formed by reaction (2) for complete flotation of the same mineral [10, 29].

$$CuFeS_2 + X^- \longrightarrow CuX + FeS_2 + e^-, E^0 = 0.096V; \quad (1)$$

$$2X^- \longrightarrow X_2 + 2e^-, E^0 = 0.009V. \quad (2)$$

The xanthate induced flotation of copper sulfides is influenced by the pulp potential and in the pH region 6 to 10 it requires oxidizing conditions (generally oxidation-reduction potential

Eh, i.e. measured with platinum indicator electrode and presented with respect to SHE, has to be in the range from -100 to 200 mV) [30].

The addition of Cu depressant ($NaHS$ or Na_2S) leads to formation of reducing conditions (a low Eh value) at which chalcopyrite surface oxidation is inhibited [31].

Under these conditions it is impossible for either xanthate or dixanthogen to be adsorbed on Cu mineral surfaces [32]. In addition, Na_2S hydlolyses – reactions (3) and (4):

$$Na_2S + H_2O \longrightarrow HS^- + OH^- + 2Na^+; \tag{3}$$

$$HS^- + H_2O \longleftrightarrow H_2S + OH^-. \tag{4}$$

Produced HS^- ions (when reach a proper concentration) replace X^- ion in copper compounds (i.e. remove the collector from the mineral's surface) – reaction (5), decrease the dixanthogen adsorption by adsorbing on the mineral surface and due to their hydrophilicity increase the hydrophilicity of the mineral thus causing inhibition of its flotation. From the other hand Na_2S (in concentrations $<$ 0.03 mol/L) does not inhibit molybdenite flotation, using petroleum-based collector and alcohol frothers, due to molybdenite good natural floatability [14, 15, 32].

$$2CuX + HS^- \longrightarrow Cu_2S + 2X^- + H^+. \tag{5}$$

Sulfide ions from Na_2S also can replace xanthate ion in CuX and react with dixanthogen (reactions 6, 7) [14, 15]:

$$2CuX + S^{2-} \longrightarrow Cu_2S + 2X^- + H^+; \tag{6}$$

$$X_2 + S^{2-} \longrightarrow S^0 + 2X^-. \tag{7}$$

The pulp potential (Eh) measured revealed that the depression of chalcopyrite occurring at enought available sulfide is due to the strong reducing environment (achieved by the Na_2S addition) leading to the decomposition and desorption of copper xanthate and the dixanthogen respectively. In a different way, the molybdenite shows less sensitivity to Na_2S addition and corresponding changes in Eh and still exhibits a high recovery when chalcopyrite was fully depressed [14].

From the other hand, over-dosage of $NaHS/Na_2S$ may cause molybdenite depressing [33]. The edge surface of molybdenite possesses high energy and electrochemical activity owing to the broken covalent S–Mo bond. At a low $NaHS$ concentration, HS^- could be oxidized as shown in reaction (8):

$$xHS^- + 1/2(x-1)O_2 \longrightarrow S_x^{2-} + H_2O + (x-2)OH^-. \tag{8}$$

Further oxidation may take place on the edge surface of molybdenite as shown by reaction (9):

$$MoS + S_x^{2-} + H_2O + 1/2O_2 \longrightarrow MoS - S_x + 2OH^-, \tag{9}$$

where S_x represents elemental sulfur or polysulfide attached to the edge surface. X-ray Photoelectron Spectroscopy (XPS) analysis confirmed the formation of S_n^{2-}/S_8 species on molybdenite surface. Polysulfide or elemental sulfur on the edge surface renders molybdenite more hydrophobic and this way enhances its flotation recovery. However, when $NaHS/Na_2S$ concentration is high the created reductive environment prevents the formation of elemental sulfur or polysulfide. For such cases, Chen et al. [31] using XPS analysis identified HS^-, S^{2-} and SO_4^{2-} on the surface of molybdenite. As a result, the hydrophobicity of the molybdenite surfaces is decreased, leading to decreased molybdenite flotation recovery.

Molybdenite has to be recovered from a copper concentrate with a high reagent content. It has been found that in order to acheve an effective copper-molybdenum separation the amount of depressant in the pulp must be maintained above certain empirically determined levels. If the depressant available in the flotation pulp is insufficient to be effective, either because an insufficient amount was initially used or because some of the depressant initially present has been consumed or lost, the collector employed to float both sulfide minerals in the initial rough flotation stage will allow the copper minerals to refloat and efficient copper-molybdenum separation will not be achieved [12]. Because of this, the molybdenum copper separation needs a high level of copper depressants and requires a complex multi-stage process, which is costly and may cause lowering of molybdenum recovery.

Instability of sulfide depressants in presence of oxygen in air and dissolved oxygen in water and the depressant adsorption on fine particles of solid phase can increase the consumption of Na_2S about 300 times. The use of nitrogen as the flotation gas in the molybdenite plant ensures stability of the reducing conditions created by the Na_2S addition. This results in about 20% decrease in the consumption of Na_2S owing to the decrease in the undesirable oxidation of Na_2S [32].

Studies carried out in Chuquicamata mine in Chile also showed that the needed depressant ($NaHS$) amount can be decreased by 48% by using N_2 instead of air. A further decrease of 21% was attained when $NaHS$ addition was controlled by potential measurement. Both lab and plant scale test verified that the application of potential measurement and control could significantly decrease the consumption of depressant. For example, laboratory scale flotation tests conducted with a 50:50% mixture of chalcocite and molybdenite showed that electrochemically achieved reducing potential in the range from -600 to -1200 mV (vs. SCE) ensured a good separation of the mentioned minerals [10].

Conducting the flotation separation with air, instead of use of nitrogen, without need of addition of high amounts of depressants of copper will simplify the flotation scheme. Conditions will be created for retention of valuable metals in the produced copper concentrate.

In addition, some problems can be avoided, such as reaction of residual lime with the phosphorus-based flotation reagents to form insoluble compounds that impede the filtration process.

Previous work [34] ensured achievement of needed reducing conditions for Cu-Mo separation by immesring stainless steel electrodes directly into the flotation cell. The study showed that similar oxidation-reduction potentials may be achieved by reagents addition and by the electrochemical impact.

In order to avoid electrodes introduction in the flotation cell and eventual problems with the cell hydrodynamics, another means is searched for ensuring reduction conditions at a decreased use of a reagent depressants. Such means could be use of catholyte of a diaphragm electrolyzer as liquid for pulp preparation in the copper-molybdenum flotation separation stage. The results from such experiments are offered in the present paper.

2. Materials and methods

Bulk copper-molybdenum-pyrite concentrate, taken from a copper flotation factory was used. The metal content was as follows: 17.9% copper, 0.31% molybdenum, and 20.3% iron. Chalcopyrite and molybdenite were the major Cu and Mo minerals, respectively. Chalcocite and bornite were identified as the minor minerals. Experiments were performed in Agitair (2.5 L) flotation cell that was found suitable by a previous study. The flotation time of 4 min was chosen also based on our previous experiments. Pulp density was set at 30% solid, having in mind findings of Zanin et al. [25], particles size was -100 +43 μm. Technical grade reagents were used. Reagents used were potassium ethyl xanthate (40 g/t), pine oil (25 g/t), diesel oil 40 (g/t), n-butanol (10 g/t), Nokes – 0.25 kg/t in the classical experiment, Na_2S in different amounts, slaked lime to reach the desired pH value. Chemical purity nitrogen was supplied by a bottle. The electrochemical impact was realized with the aid of a laboratory stabilized rectifier. The additionally grinded material was subjected to an electrochemical impact with electrodes, made of stainless steel, immersed directly into the flotation cell. The electrodes design is described elsewhere [35]. A home-made diaphragm electrolyzer was used to prepare catholyte from tap water to which some salt is added. Dimensionally stable anode (i.e. titanium covered with metal oxides) and stainless steel cathode were used. The power source was a laboratory stabilized rectifier. Figure 2 presents schematically the experiments carried out.

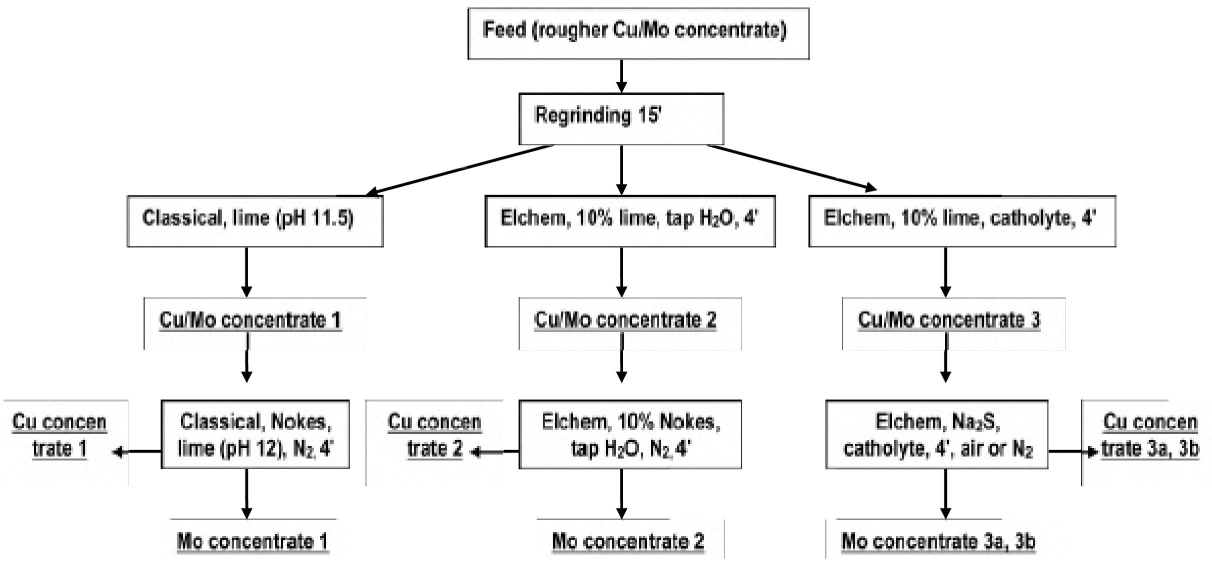

Figure 2. Scheme of the experiments.

The pH value and the oxidation-reduction potential (Eh) value of the pulp were measured with a WTW portable multi parameter 3320 device and combined pH and ORP electrodes (Pt and $Ag, AgCl$). Metals content was determined by ICP720-OES, Agilent Technologies, after proper digestion of samples. Each presented result is an average of 2 parallel experiments. Data were processes with Excel program.

3. Results and discussion

Results on the influence of the electrochemical impact on copper-pyrite selection are presented in table 1. As it can be seen, better results with respect to copper recovery are obtained at decreased lime addition and applied electrochemical impact by electrodes immersed in the pulp. This may be assigned to the fact that the achieved pulp pH value in the range of 10.0 - 10.5 was enough high to ensure the needed foam stability. At the same time, the amount of Ca^{2+} ions that present in the pulp is not too high, so as to decrease the chalcopyrite floatability. It is shown that $CaCl_2$ solutions decrease the floatability of chalcopyrite and molybdenite at pH values higher than 9 [36]. Although a little bit lower, compared to the case with immersed electrodes, copper-pyrite separation is still better in the case of catholyte use, compared to the classical case without an electrochemical impact and with lime addition to reach pH 11.5. The positive aspect of catholyte use is the avoidance of electrodes immersion directly into the flotation cell.

Results on molybdenum recovery and on the recovery of Cu in molybdenum concentrate are presented in figure 3. Figure 4 shows the Eh and pH values measured in the pulp.

As it can be seen in figure 3, when air is the flotation gas, the addition of Na_2S increases molybdenite recovery until reaching particular concentration of 20 kg Na_2S per t and further increase in the amount of added reagent does not practically improve the molybdenite flotation.

This doze of Na_2S ensured the highest depression of Cu minerals, under the given conditions. Carryng the process with N_2 as flotation gas gives best results with respect of both Mo flotation

Table 1. Cu recovery in the Cu/Mo concentrate.

No (according to figure 2)	Cu recovery, %	Fe recovery in tailing, %
1	93.89	79.32
2	96.31	84.94
3	95.44	83.87

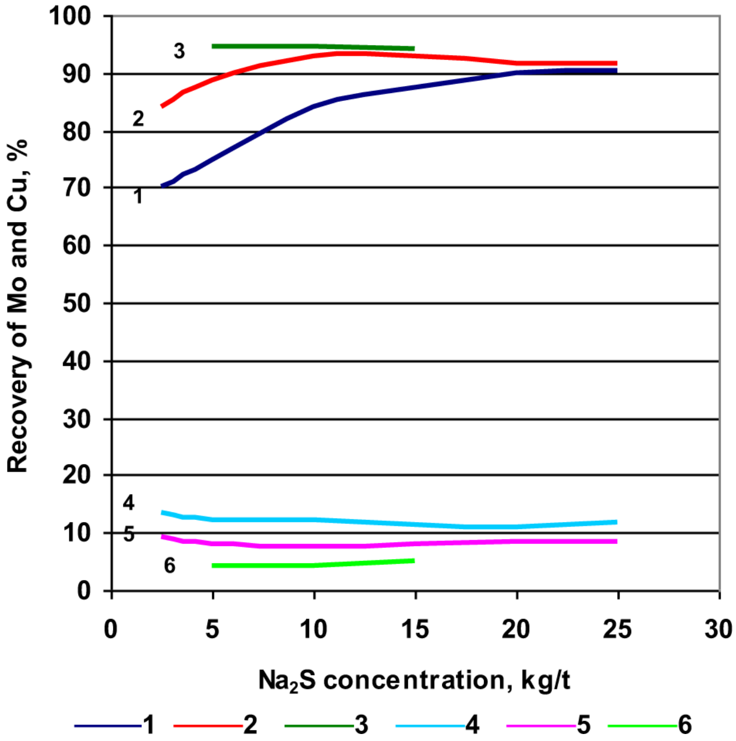

Figure 3. Recovery of Mo (higher values) and Cu (lower values) in Mo concentrate under different concentrations of added Na_2S and different conditions: 1 – Mo, air, pulp with tap water; 2 – Mo, air, pulp with catholyte; 3 – Mo, nitrogen, pulp with tap water; 4 – Cu, air, pulp with tap water, 5 – Cu, air, pulp with catholyte, 6 – Cu, nitrogen, pulp with tap water.

and Cu depression at 3-4 times lower Na_2S doze. When the pulp was prepared with catholyte, instead of tap water, under the air conditions, best results were obtained at half of the Na_2S amount used in the case of tap water. The results can be considered satisfactory both in terms of molybdenite flotation and chalcopyrite depression, although the values obtained when using nitrogen are not reached.

The best results obtained with the use of nitrogen can be explained by achieving and maintaining low values of the oxidation-reduction potential Eh of the pulp at which the molybdenite floats well (figure 4, curve 4). As a result of conducting the process with air as the flotation gas, under stirring conditions, the redox potential of the pulp increases, especially at lower amounts of added reductant. This leads to a deterioration of molybdenite flotation and at the same time a weak chalcopyrite flotation begins, as the low edge of the redox potential of chalcopyrite flotation is reached, at the respective pH values (figure 4, curve 2). Use of catholyte (with reducing properties) in pulp preparation slows the pulp Eh movement to positive values due to the air effect and thus keeps longer the suitable Eh range for molybdenite flotation and

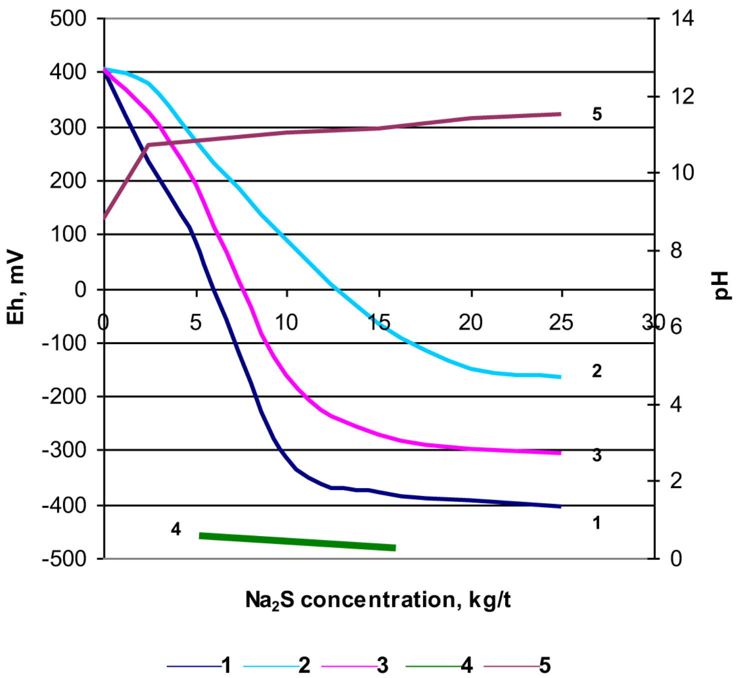

Figure 4. Eh and pH values measured in the Cu-Mo pulp under different concentrations of added Na_2S and different conditions: 1 – air, pulp with tap water, 30" after reagent addition; 2 – air, pulp with tap water, 3rd-4th min after reagent addition; 3 – air, pulp with catholyte, 3rd-4th min after reagent addition; 4 – nitrogen, pulp with tap water, 3rd-4th min after reagent addition; 5 – pH, air, pulp with catholyte, 3rd-4th min after reagent addition.

chalcopyrite depression (figure 4, curve 3).

Studies (with immersed in the pulp electrodes) showed that, at reducing potentials (Eh between -180 and -240 mV), the highest molybdenum recovery of 96-97% and the lowest copper recovery of 4-5% can be achieved [34]. Practically the same range of potentials (Eh from -160 to -270 mV at pH 10-11) has been confirmed as optimal for conducting electrochemically assisted (by immersed electrode or catholyte-assisted) copper-molybdenum selection by the experiments described here.

Potentials in the range of -100 to -200 mV, on hydrogen scale, (obtained by reagents addition) were reported as the optimal for copper-molybdenum separation [37]. Sepalveda-Suarez and Castro studied the effect of Eh on the selective flotation of molybdenite from chalcopyrite by using fresh bulk Cu–Fe–Mo concentrate, taken directly from the "El Salvador" industrial plant, Anamol-D (a Cu depressant), and N_2 as a flotation gas [38]. They found that Cu mineral depression was effective at potentials below -180 to -200 mV. The high effect of Eh on Mo recovery was noticed in the potential range from +20 to -280 mV, with a fast recovery of Mo in concentrate with a high grade in the potential range from -180 to -280 mV.

About 100 mV more reducing potentials (obtained by addition of two types of Na_2S – of mineral origin and of chemical nature) were reported as the range of best copper-molybdenum selection by Kolahdoozan and Noori [39]. The highest achieved molybdenum recovery was 93% and the lowest copper recovery was 4-15%. Addition of extra amounts of Na_2S did not change considerably the potential range reached. At more oxidizing potentials (more positive than about -200 mV), similarly to the found by us, the Cu recovery started and the Mo recovery dropped.

Smith, Davey and Bruckard pointed the potential of -340 mV as the most suitable one for the molybdenum concentrate production [40].

Mehrabani et al. also studied the effect of pulp potential on the flotation separation of chalcopyrite and molybdenite [5]. The potential was changed by the addition of Na_2S and/or by using nitrogen. It is reported that the addition of 16 kg/t Na_2S into the flotation pulp under aeration conditions initially decreased the pulp potential Eh from +450 to -375 mV. Using air as the flotation gas caused gradual increase of the pulp potential to -178 mV. A molybdenum recovery of 91.74% (at only 0.44% recovery of copper minerals) was achieved at a Na_2S consumption of 16 kg/t. The use of N_2 instead of air helped to decrease the consumption of Na_2S to 6 kg/t (pH = 10.5, Eh remained stable in the range of -100 to -200 mV at the end of flotation), where molybdenite recovery of 92.88% was achieved at a separation efficiency of 90.03%.

Bahrami et al. measured the Eh range of -370 to -390 mV in the rougher flotation circuit of the molybdenum plant of the Sungun copper–molybdenum processing-complex [41].

Recoveries of Cu and Mo in final concentrates, obtained under different conditions, are shown in table 2.

Table 2. Recoveries of Cu and Mo in final concentrates obtained under different conditions.

Conditions	Cu recovery in final Cu concentrate*, %	Mo recovery in final Mo concentrate*, %
Classical	No 1 - 93.54	No 1 - 92.75
Electrochemical impact-immersed electrodes, tap water, 10% Nokes, N_2	No 2 – 95.88	No 2 – 94.57
Electrochemical impact-catholyte, Na_2S – 10 kg/t, air	No 3a – 95.03	No 3a – 92.99
Electrochemical impact-catholyte, Na_2S - 5 kg/t, N_2	No 3b – 95.19	No 3b – 94.33

* Numbers – according to figure 2.

The lowest recoveries are obtained under "classical" conditions, with lime and Nokes addition and pH 12 in the Cu-Mo separation stage, although the Eh values were in the suitable Eh range. Flotation with an electrochemical impact gives better results with the best one with electrodes immersed in the pulp. However, the results obtained with use of catholyte are also promising. The electrochemical impact does not ensure achieving as high pH value of the flotation pulp, as the lime addition. This is favorable for Cu minerals depression, besides reaching the suitable Eh ranges. Mehrabani et al. [5] has pointed that Cu minerals flotability increases 3-4 times with the pH increase from 10.5 to 12.5.

Decreased lime use in Cu/Py selection and its avoidance in the Cu/Mo selection most probably lead to better preservation of the molybdenite inherent hydrophobicity. Less Ca-containing precipitation species are expected to be generated. The adsorption of these species is found to cover molybdenite edges. The adsorption of calcium species decreases the contact angle of the molybdenite particles thus reducing their hydrophobicity and leading to a decrease in the floatability of these particles [27,42]. The depression caused by Ca^{2+} ions is proportional to their concentrations [36]. It is found that both copper and molybdenum recoveries were lower in the presence of Ca^{2+} ions in concentrations higher than 10^{-2} M, in particular at pH > 10 [25].

4. Conclusions

1. Effective copper-pyrite and copper-molybdenum flotation selection can be achieved (at significantly reduced amounts of reagents used) with the aid of an electrochemical impact

achieved both by electrodes immersed in the flotation pulp or by using catholyte for pulp preparation.

2. The optimum Eh potential range for the Mo recovery (92-93%) and the lowest copper recovery (7-8%) in molybdenum concentrate is determined as -160 to -270 mV and pH 10-11 under air conditions. Molybdenum flotation separation from copper can be effective by controlling the Eh and pH ranges of the flotation pulp either by reagents addition and/or by the electrochemical impact.
3. Minimization of reagents' use or their replacement by an electrochemical impact exhibits several advantages: easier process control (by the applied electrical energy); a possibility for faster and facilitated response to the changeable minerals that feed the flotation process, including impoverished and complex ores; improved environmental impact.

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Experimental tests of the over-columned plates of the precast building frame

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Experimental tests of the over-columned plates of the precast building frame

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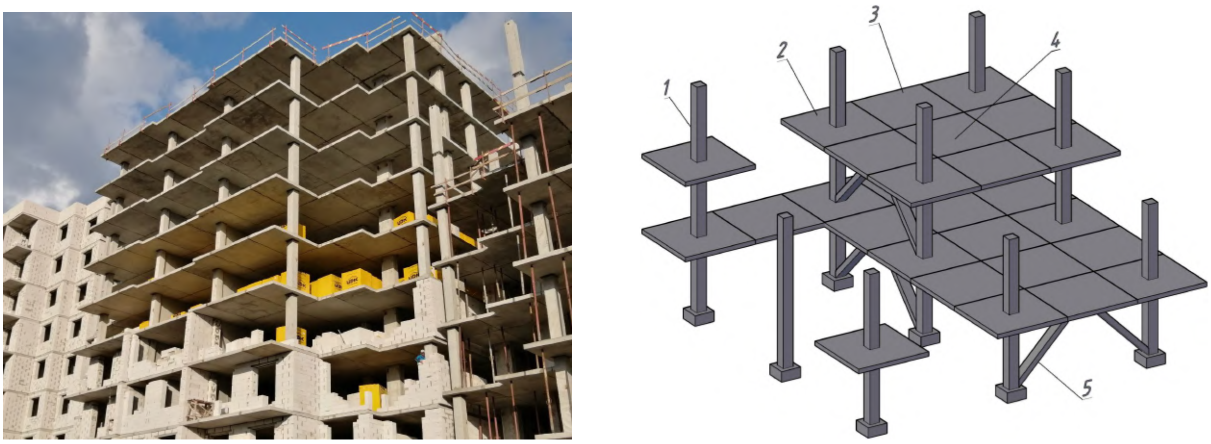
Abstract. The construction of a precast flat plate frame of buildings is considered for its implementation during the restoration of the housing stock of Ukraine. The analysis of the precast flat plate floor system of the frame structural system by using the yield line method showed that in the ultimate state the floor is divided into separate discs along the joints of precast plates. This makes it possible to determine the load-bearing capacity of the floor by considering each plate taking into account their supporting and loading conditions. Based on this, experimental tests of three full-size over-columned plates of a precast flat plate floor system are carried out, according to the diagram closest to the actual scheme of their operation as part of the floor. The general deflections of the plates, moments of crack formation and width of their opening, as well as strains of concrete and reinforcement in characteristic cross-sections of the plates are determined. Based on the experimental tests, the accepted failure scheme of the over-columned plates of the precast flat plate floor system is confirmed and the feasibility of applying the yield line method to the calculation of their bearing capacity is proven.

1. Introduction

To date, renewal of the housing stock of Ukraine has become one of the most urgent tasks in the field of construction. This task can be solved by introducing modern structural systems in the erection of buildings and structures. It is quite possible and expedient to apply the structural system of buildings based on a precast flat plate frame [1] to solve this problem.The benefits of using the named system are proven: construction speed increases by 50% due to the use of industrial precast reinforced concrete structures; installation of reinforced concrete members does not depend on weather conditions and can be carried out throughout the year; starting a production line for the manufacture of precast members is quite simple and can be done in the shortest possible time; the frame has features that allow each building to have unique architectural forms, which makes the urban landscape more attractive and diverse; architectural and planning solutions meet high aesthetic requirements, provide comfort and a high level of microclimate; the cost of 1 square meter of housing is reduced by almost 40% compared to buildings using traditional structural systems.

The precast flat plate frame structural system of buildings is being widely implemented in residential construction (figure 1). The flat plate of the structural system is arranged on columns and is a simple structure consisting of reinforced concrete plates of the same thickness and shape. This composition of floor components simplifies the process of formwork and production and significantly speeds up the construction of objects. The main structural members of the flat plate

Figure 1. One of the new buildings of precast flat plate frame structural system in Poltava.



(a) (b)

Figure 2. Precast flat plate frame structural system of buildings: (a) a building under construction and (b) the general view of the structural system: 1 – column; 2 – over-columned plate; 3 – inter-columned plate; 4 – middle plate; 5 – linear brace.

frame structural system are columns and plates (figure 2). Flat floors are directly connected to columns without the use of protruding members, which provides the opportunity to freely adapt the architectural and planning solutions of buildings for any purpose.

The design of flat plate frame structural systems is usually carried out by dividing them into flat orthogonally located frames [2, 3]. At the same time, the frame is considered as a set of frames with rigid nodes. Over-columned and inter-columned floor plates in the range of each row of columns are considered as continuous crossbars of the frames, and therefore are designed as continuous beams at equalized moments based on consideration of the redistribution of forces in the ultimate limit state. The middle plate is designed as two-way slab according to the limit equilibrium method, taking into account the fastening way in the supporting circuit.

Meanwhile, as practice shows, the work of members in the framework of a precast flat plate structural system differs from that implemented in the mentioned design schemes. In particular,

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in the precast version of the structural system the destruction scheme of its members is formed depending on the design of the joints of the precast members. At the same time, the schemes of deformation of floor plates are accepted as for plates with special fastening conditions. As evidenced by works [1, 4], for the strength design of plates supported along the contour, it is quite expedient and convenient to use the yield line method, which allows taking into account the actual conditions of fastening, reinforcement and the nature of the destruction of members.

The application of the yield line method [5–9] to the calculation of the bearing capacity of reinforced concrete plates is considered for plates made of fiber concrete [10, 11], plates supported on two adjacent sides [12], plates with an irregular grid of columns [13], plates with the destruction of individual columns [14], as well as in many other cases [15–19]. Data of theoretical calculations in the mentioned works are supported by experimental results. Experimental data [20] for plates of the flat plate frame structural system are scarce today, so there is a need to experimentally investigate the members of this system in order to confirm the proposed fracture schemes [4].

2. Construction of experimental samples of over-columned plates

Three experimental full-scale samples of over-columned floor plates were used for conducting experimental tests. The plate samples had nominal dimensions of 2980×2980×160 mm. The specified geometric characteristics are adopted for the purpose of their compliance with the unified dimensions of precast reinforced concrete members of the flat plate floor system. The design of the test sample and its geometric dimensions are shown in figure 3. The reinforcement scheme of the experimental sample of the over-columned plate is displayed in figure 4. The characteristics of concrete and reinforcing steel used in the manufacture of the samples of the experimental over-columned plates are specified in table 1.

Table 1. Characteristics of materials used in the manufacture of experimental samples of over-columned plates.

Physical and mechanical characteristics of materials	Plate PO-1	sample PO-2	code PO-3
Reinforcement A500C			
Ø18, σ_y, MPa	600	600	600
Ø14, σ_y, MPa	610	610	610
Ø10, σ_y, MPa	620	620	620
Ø8, σ_y, MPa	630	630	630
Concrete C25/30			
f_{cd}, MPa	17	17	17

The production of the tested samples of the over-columned plates is divided into stages: at the first stage, reinforcement products are made for laying in the formwork, at the second stage, concreting is carried out A500C class bars are used as the principal reinforcement of the plates. The over-columned plates are reinforced with a spatial reinforcing cage (figure 4), which includes the upper and lower plane meshes and embedded support structure. The upper mesh was assembled by hand in conjunction with the support structure of the plate in the form of a steel clip and vertical cages welded to it.

The over-columned plates are made of heavy concrete, which has an average density ranging from 2200 kg/m^3 to 2500 kg/m^3. Strength class of concrete is C25/30 [3]. The over-columned

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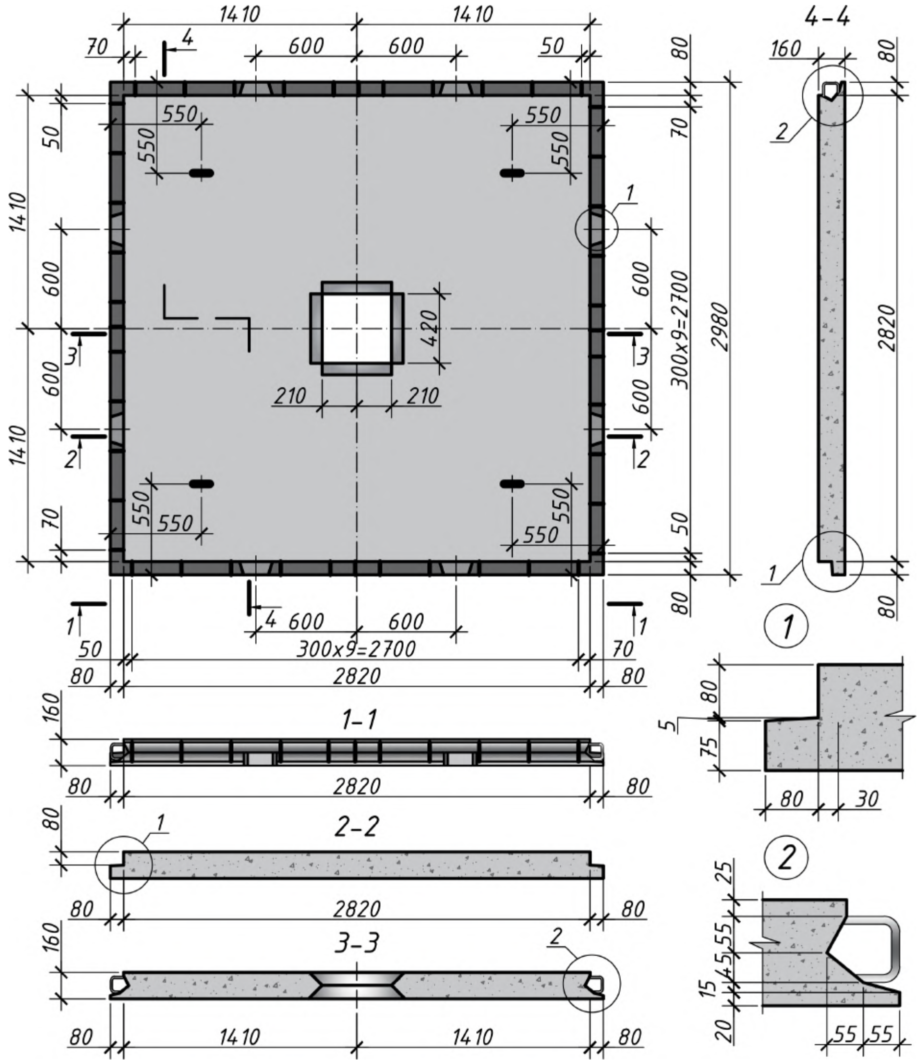


Figure 3. Design of experimental samples of over-columned plates.

plates are reinforced with reinforcing components made of of A500C steel, which included (positions on figure 4):

1 – the plane M-1 mesh made of steel bars of a diameter 14 mm, a length of 2800 mm, connected to an embedded support structure SSE-1, in which 3 outlets of reinforcement with a diameter of 18 mm are arranged on four sides (figure 5);

2 – the plane mesh M-2 made of steel bars with a diameter of 8 mm and a length of 2960 mm;

3 – bent bars B-1 with a diameter of 12 mm, a length of 800 mm, a bending angle of 90°;

4 – the spatial cage CS-1 made of steel bars with a diameter of 12 mm and a length of 850 mm and reinforcing bars with a diameter of 4 mm and a length of 300 mm;

5 – bent bars B-2 with a diameter of 12 mm and a length of 800 mm.

To determine the physical and mechanical characteristics of the reinforcing steel (table 1) the passport data provided by the manufacturer are used.

The production of reinforcing cages, meshes and embedded parts, as well as concreting of over-columned plates was carried out at the plant of reinforced concrete products of "Combinat of industrial enterprises" in the village of Tereshki of Poltava region.

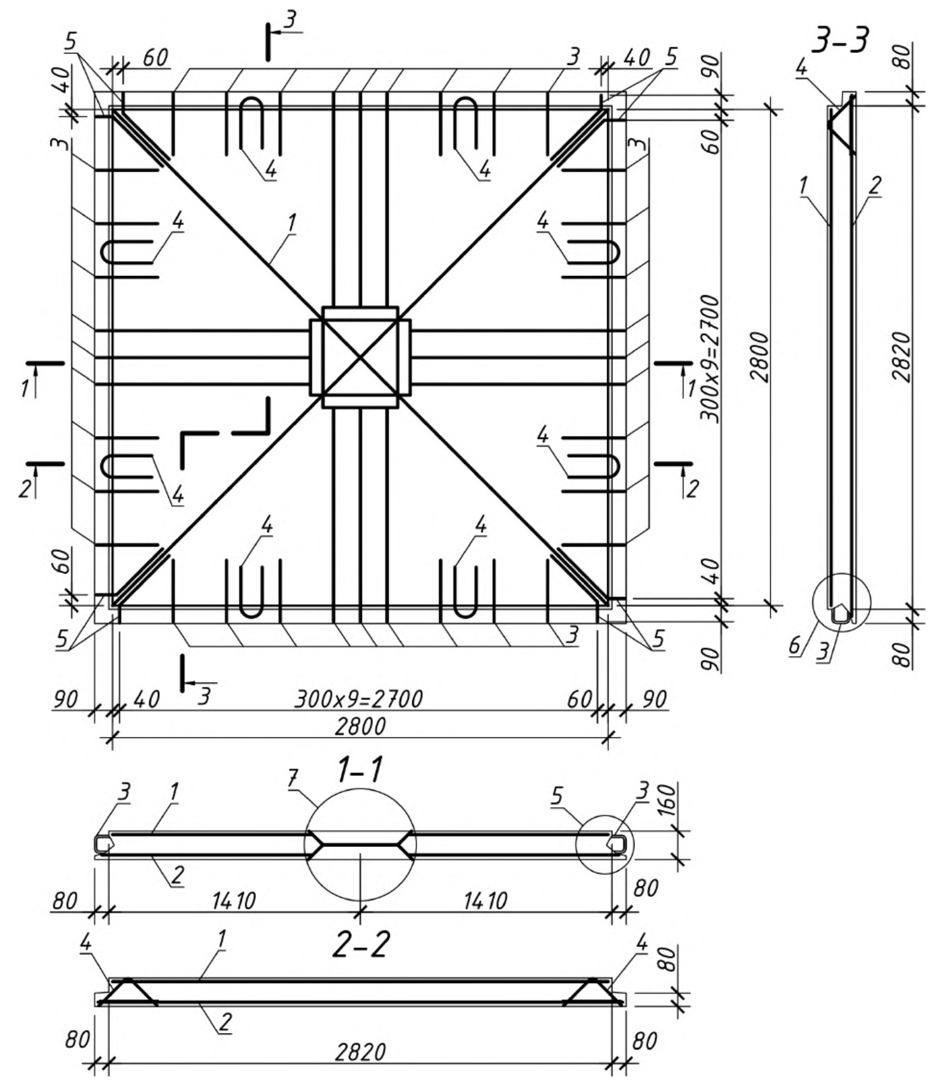


Figure 4. Reinforcing scheme of the experimental sample of the over-columned plate: 1 – mesh M-1; 2 – mesh M-2; 3 – bent bar B-1; 4 – spatial cage CS-1; 5 – bent bar B-2.

The concrete mixture was produced directly at the concrete unit of the enterprise. Dosing of components took place in automatic mode. Laying of the concrete mixture was carried out using a dosing device. After laying the concrete mixture in the metal formwork, it was compacted with deep vibrators. Hardening of the concreted samples took place under the conditions in the steaming chamber. After the concrete reached full strength, the elements were released from the formwork. After that, the tested samples of the over-columned plates were transported to the laboratory of the Department of Building Structures of the National University "Yuri Kondratyuk Poltava Polytechnic" for testing.

In the laboratory, strain gauges with a base of 50 mm and 20 mm, respectively, were pasted on the concrete and on the reinforcing bars of the experimental plate samples in the zones of their possible destruction. Gluing of strain gauges was carried out using BF-2 glue, following all recommendations for performing such works. Previously, the surface of concrete and reinforcing bars in the areas where strain gauges were installed was cleaned, polished, degreased with a solvent and primed with glue.

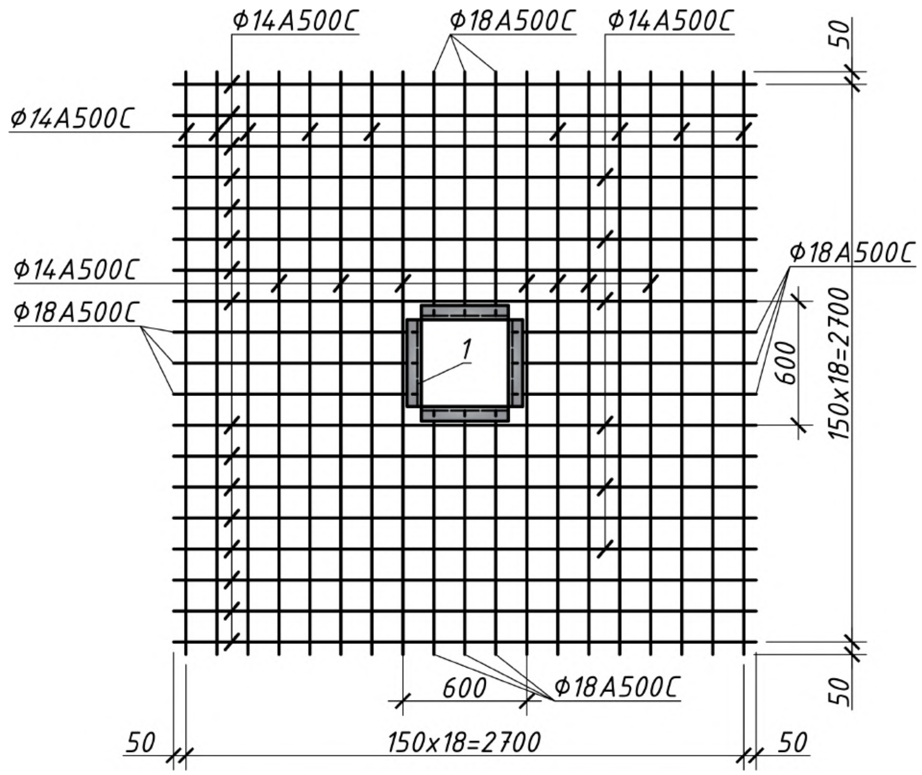


Figure 5. Structure of the reinforcing mesh M-1 of the over-columned plate: 1 – embedded support structure SSE-1.

3. Methodology of over-columned plates tests

Control tests of full-scale samples of over-columned plates is carried out on a specially designed stand according to the developed scheme (figure 6). It is impossible to simulate the supporting and loading scheme of the plate, which would absolutely correspond to the real work of the plate as a member of a precast flat plate floor system. That is why the testing scheme of over-columned plates is adopted in such a way that it allowed implementing the design fracture scheme accepted on the basis of the yield line method, which is realized in the composition of a flat plate floor system [4].

A stand with a hydraulic jack was used to load the experimental samples of the over-columned plates. The pressure in the system was increased using a mobile pumping station. A pressure gauge, which was previously tared, was used to measure the load. When conducting static load tests, the following measuring devices were used: watch-type deflection gauge 6PAO with a division value of 0.01 mm (figure 6) for measuring linear displacements; strain gauges for measuring concrete and reinforcement deformations (figure 7); MPB-2 microscope with a resolution of 0.05 mm for measuring the crack opening width.

The general appearance of the installation during the testing of the over-columned plate samples and the location of all measuring devices is presented in figure 8.

4. Over-columned plates tests results

The testing of the over-columned plates PO-1, PO-2, and PO-3 was carried out to an external load of 320 kN, 360 kN, and 400 kN, respectively. These values of load made up about $0.55F_{Rd}$, $0.6F_{Rd}$, and $0.7F_{Rd}$, respectively, where F_{Rd} = 580 kN – the design value of the destructive load, calculated by the yield line method for the over-columned plate according to [4] taking

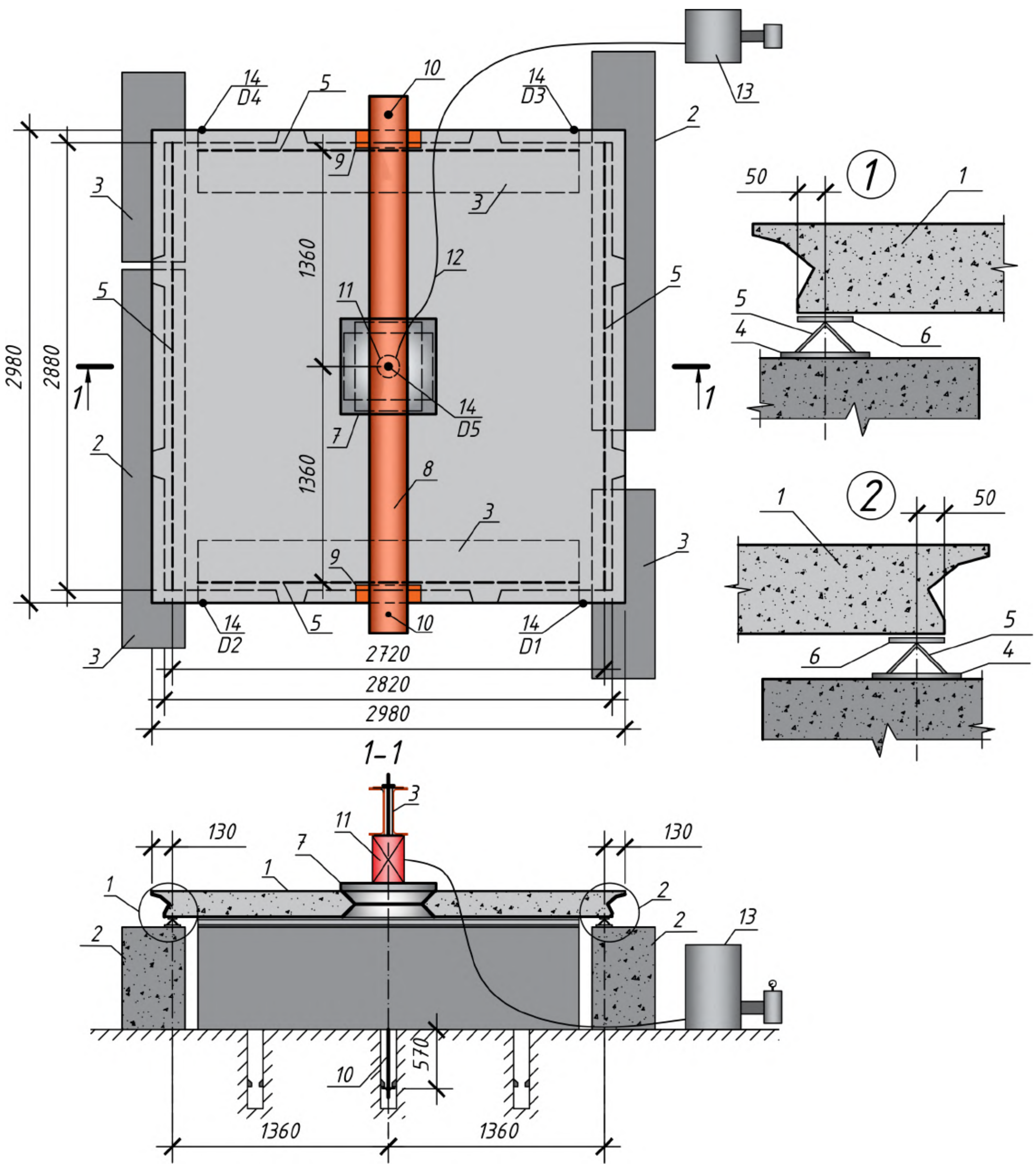
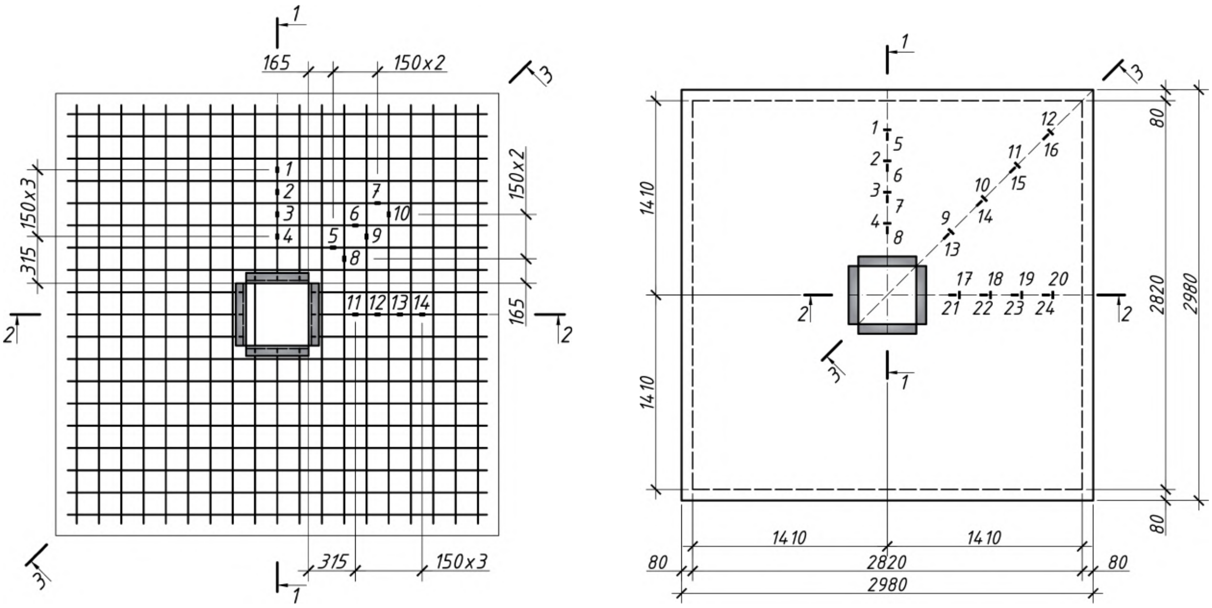


Figure 6. Test scheme of the over-columned plate: 1 – plate PO; 2 – supporting element (concrete block FB 24.6.5); 3 – supporting element (concrete block FB 12.6.5); 4 – steel plate (strip 150×10); 5 – unmovable hinged support (steel angle bar 75×5); 6 – steel plate (strip 100×8); 7 – steel plate (strip 600×5); 8 – traverse (2 channels No. 30); 9 – temporary support for the traverse; 10 – steel bar (Ø30A240); 11 – hydraulic jack F = 500 kN; 12 – oil pipeline; 13 – pumping station; 14 – 6PAO watch-type deflection gauge.

into account calculated values of ultimate strains of concrete in compression.

In the course of the tests, it was noted that the character of the formation of cracks and the deflections growth of various test samples of plates PO-1, PO-2 and PO-3 did not differ significantly, since all the test samples had the same geometric dimensions and were tested according to the same supporting and loading scheme (figure 6).

When testing the PO-1 plate, the first crack was formed near the supporting opening along



(*a*) (*b*)

Figure 7. Strain gauges arrangement diagram: (*a*) on the principal reinforcement of the over-columned plate: 1 ... 14 – gauges with a base of 20 mm and (*b*) on the concrete of the over-columned plate: 1 ... 24 – gauges with a base of 50 mm.

(*a*) (*b*)

Figure 8. General view of the over-columned plate PO-1 during the test: (*a*) top view and (*b*) side view.

one of the diagonals of the plate under a load of 120 kN ($0.2F_{Rd}$). When the load increased, it began to open, and then another crack was formed along the other diagonal of the plate. During loading, these cracks extended along the diagonals in the direction from the center of the plate to its edges. The opening width of the cracks in the plate under a load of 120 kN was 0.1 mm, under a load of 320 kN ($0.55F_{Rd}$) the width of the crack reached 2 mm.

During the experimental tests of the PO-1, PO-2, and PO-3 the dependence of the deflections on the magnitude of the external load was studied. The readings of the deflection gauges (D1 – D5), the location of which is shown in figure 6, were recorded for all slab samples up to a load value of 320 kN. Graphs of the dependence of deflections of full-scale over-columned plates on

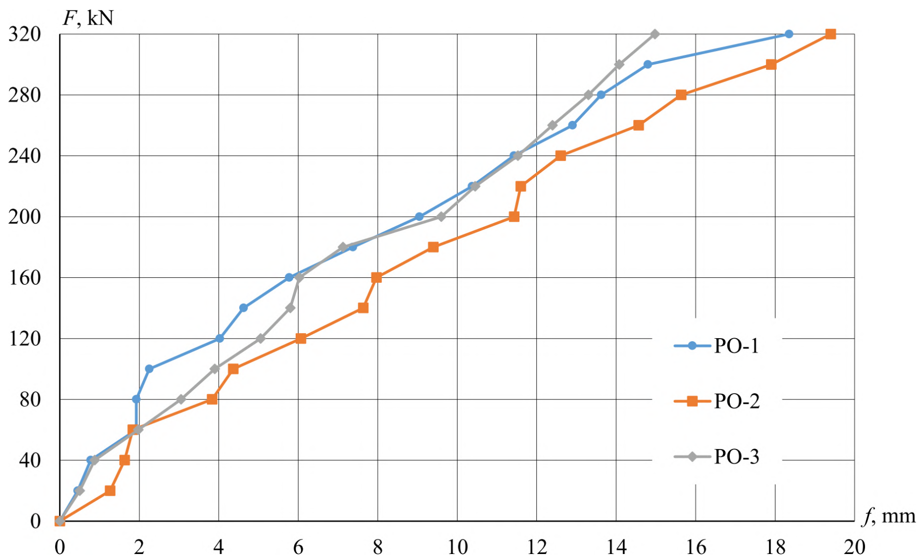


Figure 9. Growth of the total deflection of the over-columned plates during the test.

the value of the external load are shown in figure 9.

It can be seen from the graphs (figure 9), up to a load value of 40 kN ($0.07F_{Rd}$) in PO-1 and PO-3 slabs and 60 kN ($0.1F_{Rd}$) deflections in the plates grew much more slowly than after this level, which is explained by the influence concrete work in the tensile zone of the plate by the amount of its deflections. As long as the concrete in the tensile zone of the plate perceives the tensile forces, the deflections grow more slowly, but as soon as the tensile forces cease to be perceived by the concrete, due to the formation of cracks in it, the deflections begin to grow faster.

The specified load levels can serve as moments of crack formation in the tensile zone of the over-columned plate. In addition, by analyzing the graphs in figure 9, it can be concluded that the dependence of the deflections on the load level is directly proportional. That is, the dependence of the deflections on the load on the graphs is linear, when the principal reinforcement of the plate, located in its tensile zone, works elastically.

The graphs (figure 9) show that at the external load level of 280 kN ($0.5F_{Rd}$) the deflections of all test samples of the over-columned plates are the closest in terms of values. The deflection values for PO-1, PO-2 and PO-3 plates are 13.9 mm (l/209) and 14.9 mm (l/195) and 13.9 mm (l/209), respectively. The maximum measured deflections of plates PO-1, PO-2 and PO-3 under a load of 320 kN ($0.55F_{Rd}$) were 18.2 mm (l/159), 18.4 mm (l/158) and 15.6 mm (l/186) respectively.

When conducting experimental studies, the strains of concrete and reinforcement were measured on one of the four quarters of the plate (figure 7), since the plate is symmetrical with respect to two mutually perpendicular axes of symmetry passing through the center of gravity of the structure. This made it possible to study sufficiently the features of the stress-strain state of the test samples.

The regularity of the distribution of deformations can be traced on the graphs of the dependence of the strains ϵ_s of the tensile reinforcement on the value of the external loading F, constructed based on the results of experimental studies (figure 10, figure 11).

The graphs (figure 10, figure 11) show that the strains of the reinforcement depending on the load had different values in different areas. From the very beginning of loading, the maximum strains were observed in section 3-3, and with further loading, these strains in the diagonal direction (section 3-3) significantly increased and the difference between them and strains in the

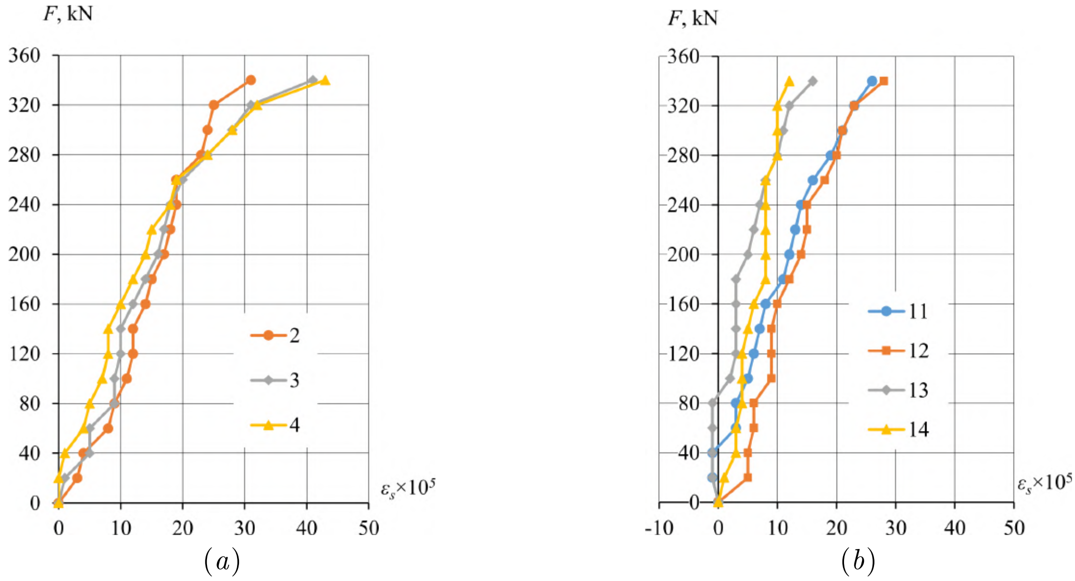


Figure 10. Strains of the principal reinforcement of the over-columned plate PO-1 during loading: (a) in section 1-1 and (b) in section 2-2.

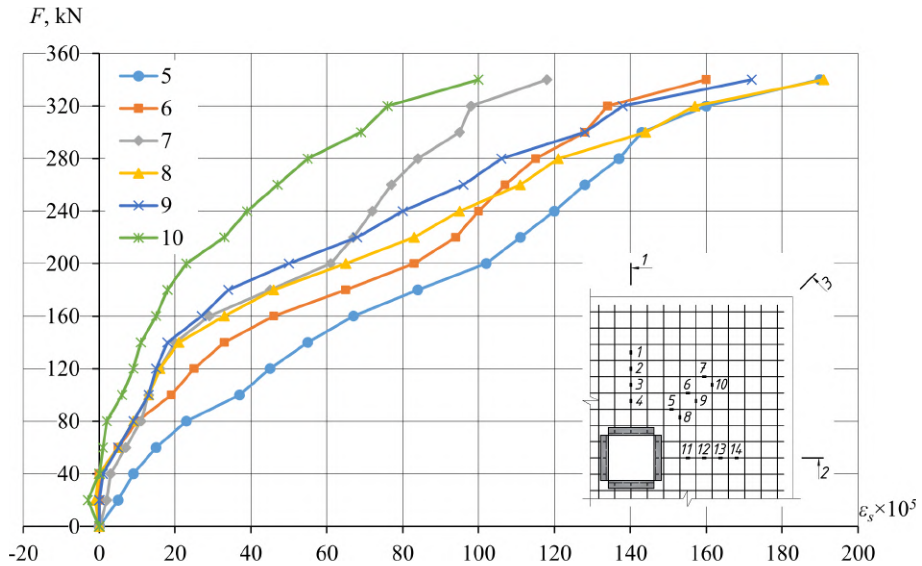


Figure 11. Strains of the principal reinforcement of the over-columned plate PO-1 during loading in section 3-3.

longitudinal and transverse directions (sections 1-1 and 2-2) enlarged considerably.

As it can be seen from graphs in figure 10, in sections 1-1 and 2-2 the bars work proportionally according to the perceived load. At the same time, the values of their strains in the PO-1 slab under a load of 320 kN ($0.55F_{Rd}$) are 10×10^{-5} – 32×10^{-5} ($0.03\epsilon_{s0}$ – $0.1\epsilon_{s0}$), in the PO-2 slab under a load of 360 kN ($0.6F_{Rd}$) – 9×10^{-5} – 37×10^{-5} ($0.03\epsilon_{s0}$ – $0.1\epsilon_{s0}$), in the PO-3 slab under a load of 400 kN ($0.7F_{Rd}$) – 3×10^{-5} – 23×10^{-5} ($0.03\epsilon_{s0}$ – $0.08\epsilon_{s0}$), where $\epsilon_{s0} = \sigma_y/E_s = 600/210000 = 286 \times 10^{-5}$ – strains of reinforcement at the yield point (table 1). Therefore, it is possible to draw a conclusion about the savings reserves of these bars.

Examining the graphs of reinforcement strains in cross-section 1-1 (figure 10, a) at the locations of gauges 1-4, it may be concluded that with the gradual approach to the supporting opening, the strains of the bars in the tensile zone of the plate increase slightly. At that time, in section 3-3 (figure 11), a significant increase in strains is observed as the reinforcing bars approach the opening.

The graphs of the strains of reinforcing bars in the diagonal section 3-3 (figure 11) up to the strain value of 20×10^{-5} $(0.07\epsilon_{s0})$ have a significantly greater angle of inclination to the horizontal axis than after reaching this value. This indicates a more intensive reinforcement deformation in the further range, which is explained by the beginning of the formation of cracks in tensile concrete. At the same time, the reinforcing bars reach the mentioned strain values at different values of the external load from 70 kN to 170 kN. The bars closest to the supporting opening are the first to reach the indicated strain values. Therefore, it can be predicted that the failure of the slab will begin when the yield point is reached, first, in the reinforcing bars that pass around the plate's opening.

The maximum values of tensile strains of the principal reinforcement in the diagonal section 3-3 were 160×10^{-5} $(0.6\epsilon_{s0})$ under a load of 320 kN $(0.55F_{Rd})$ in the plate PO-1, 181×10^{-5} $(0.6\epsilon_{s0})$ at a load of 360 kN $(0.6F_{Rd})$ in the PO-2 slab, 178×10^{-5} $(0.6\epsilon_{s0})$ with a load of 400 kN $(0.7F_{Rd})$ in the PO-3 plate and the minimum values were 76×10^{-5} $(0.3\epsilon_{s0})$, 98×10^{-5} $(0.3\epsilon_{s0})$, 111×10^{-5} $(0.4\epsilon_{s0})$, respectively.

During the experimental studies of full-scale over-columned plates PO-1, PO-2 and PO-3, in addition to strains of reinforcement ϵ_s in the tensile zone of the plate, strains of concrete ϵ_c located in the compressed zone were also studied.

From the very beginning of the experimental research, during the loading of the test samples of the over-columned floor plates, the maximum values of the concrete compressive strains were observed at the locations of the gauges 1–4, 9–12, and 17–20 (figure 13, figure 14), respectively, in sections 1-1, 2-2, 3-3.

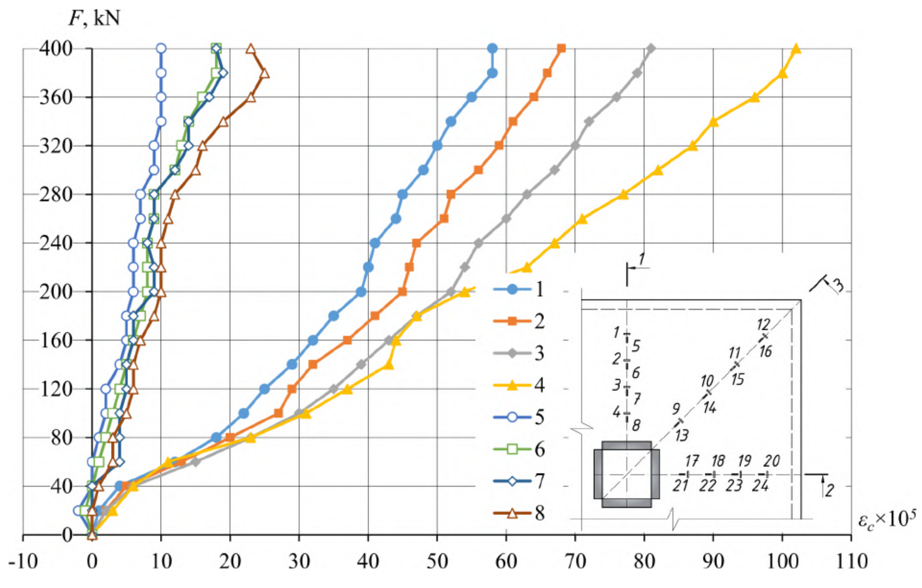


Figure 12. Compressed concrete strains of the PO-3 over-columned slab during loading in section 1-1.

By analyzing the nature of the graphs in figures 12–14, it can be noted that the strains of concrete across sections 1-1, 2-2 and 3-3 occurred more intensively than in the longitudinal direction. The specified difference is typical for all sections. The maximum values of compression strains of concrete in the transverse direction in sections 1-1, 2-2 and 3-3 were:

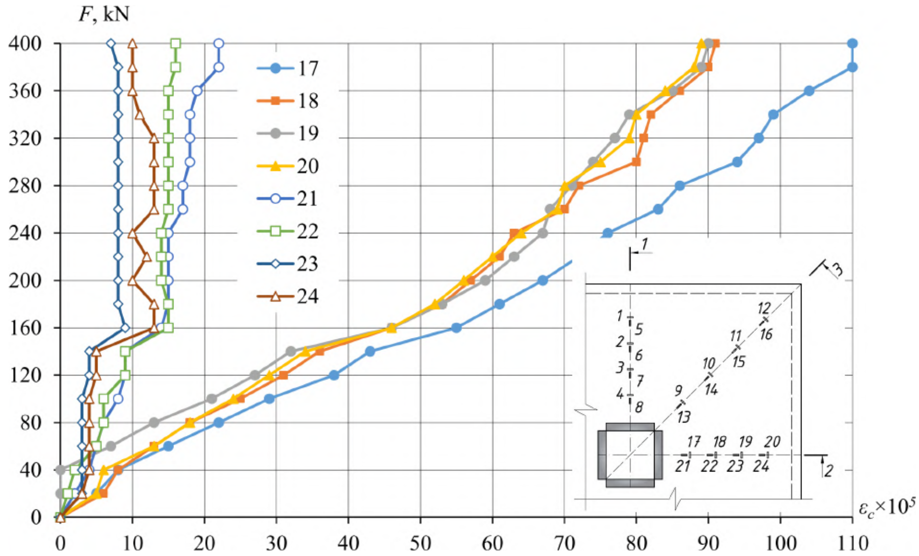


Figure 13. Compressed concrete strains of the PO-3 over-columned slab during loading in section 2-2.

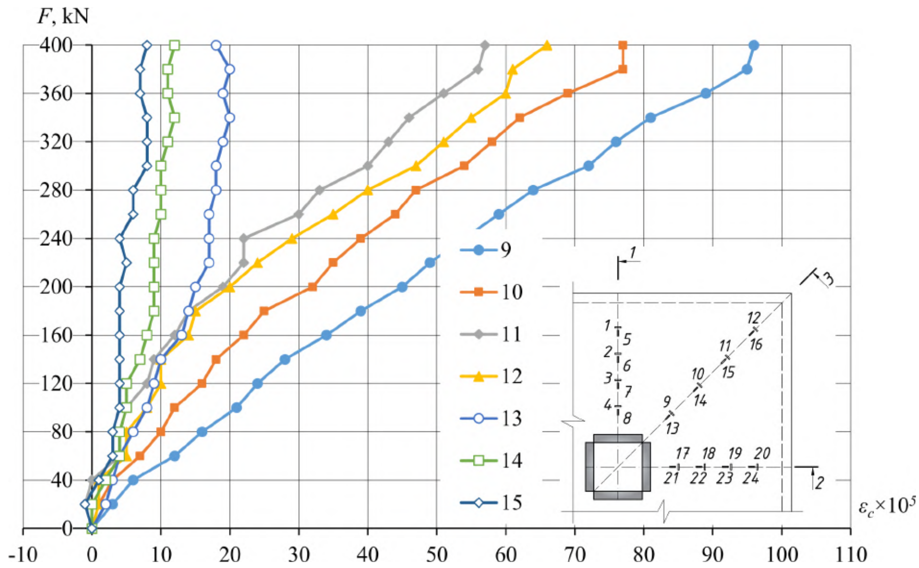


Figure 14. Compressed concrete strains of the PO-3 over-columned slab during loading in section 3-3.

- in the PO-1 plate under a load of 320 kN ($0.55F_{Rd}$), respectively $64 \times 10^{-5}(0.2\epsilon_{cu1})$, $110 \times 10^{-5}(0.3\epsilon_{cu1})$ and $70 \times 10^{-5}(0.2\epsilon_{cu1})$;
- in the PO-2 plate under a load of 360 kN ($0.6F_{Rd}$), respectively $52 \times 10^{-5}(0.1\epsilon_{cu1})$, $89 \times 10^{-5}(0.3\epsilon_{cu1})$ and $84 \times 10^{-5}(0.2\epsilon_{cu1})$;
- in the PO-3 plate under a load of 400 kN ($0.7F_{Rd}$), respectively $102 \times 10^{-5}(0.3\epsilon_{cu1})$, $110 \times 10^{-5}(0.3\epsilon_{cu1})$ and $96 \times 10^{-5}(0.3\epsilon_{cu1})$, where $\epsilon_{cu1} = 350 \times 10^{-5}$ – ultimate value of strains of concrete C25/30 according to [3].

The maximum values of compression strains of concrete in the longitudinal direction in sections 1-1, 2-2 and 3-3 were:

- in the PO-1 plate under a load of 320 kN ($0.55F_{Rd}$), respectively $29 \times 10^{-5}(0.08\epsilon_{cu1})$, $23 \times 10^{-5}(0.07\epsilon_{cu1})$ and $30 \times 10^{-5}(0.08\epsilon_{cu1})$,
- in the PO-2 plate under a load of 360 kN ($0.6F_{Rd}$), respectively $17 \times 10^{-5}(0.05\epsilon_{cu1})$, $10 \times 10^{-5}(0.03\epsilon_{cu1})$ and $9 \times 10^{-5}(0.03\epsilon_{cu1})$,
- in the PO-3 plate under a load of 400 kN ($0.7F_{Rd}$), respectively $23 \times 10^{-5}(0.07\epsilon_{cu1})$, $22 \times 10^{-5}(0.07\epsilon_{cu1})$ and $18 \times 10^{-5}(0.05\epsilon_{cu1})$.

Thus, the difference between strains in the transverse and longitudinal directions for all plates ranged in section 1-1 from 69% to 82%, in section 2-2 from 79% to 93%, in section 3-3 from 64% to 84%.

Examining the graphs of concrete strains by gauges perpendicular to the section, it can be concluded that with the gradual approach to the supporting opening, the values of strains of concrete in the compressed zone of the slab increase significantly. At the same time, in the longitudinal direction (according to the gauges located along the cross-sections), this tendency is much less pronounced. By comparing the graphs of strains of compressed concrete and tensile reinforcement, it should be noted that in concrete the distribution of strains in cross-sections 1-1, 2-2 and 3-3 does not have a considerable difference, in contrast to the reinforcement, in which the strains in cross-section 3-3 are significantly larger in comparison with strains in sections 1-1 and 2-2. The indicated trend is clearly demonstrated in the fields of strain distribution over the area of the experimental plates, built according to the results of experimental studies (figures 15, 16).

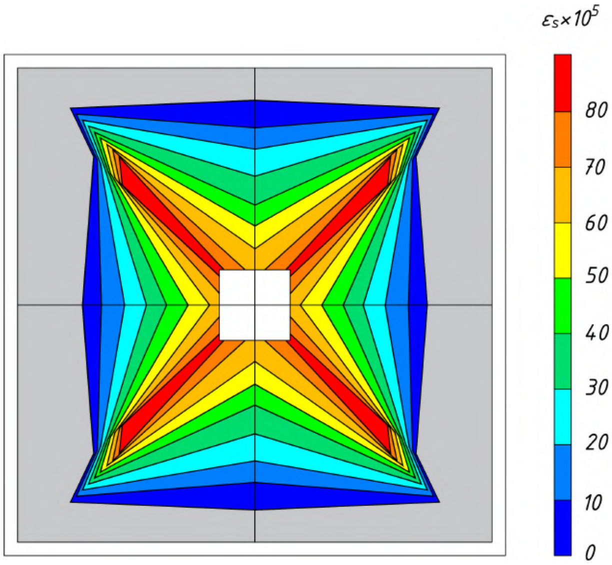


Figure 15. Fields of strains' distribution of the principal tensile reinforcement of the PO-1 plate at the moment of destruction.

Figures 15, 16 illustrate that the over-columned plate when working as part of the floor system has the largest values of strains of tensile reinforcement in diagonal directions. At the time of failure, yield lines will form along the diagonals of the plate, which are characterized by reaching the yield point in the tensile reinforcement.

The yield phenomenon, which begins in the most stressed places of the plate – around the supporting opening – with the load increasing will spread to the entire reinforcement along its diagonals, forming lines along which the bending moment reaches the ultimate value. At the same time, the plate will be divided into separate disks connected by diagonal yield lines, which

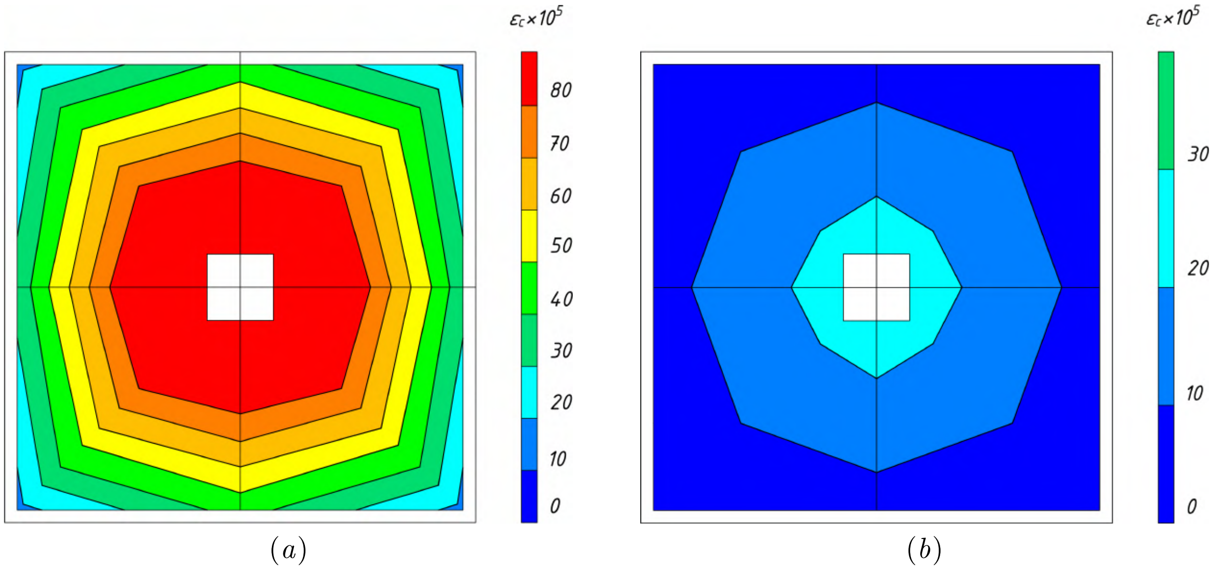


Figure 16. Fields of strains distribution of the compressed concrete of the PO-3 plate at the moment of destruction: (*a*) in the direction transverse to sections 1-1, 2-2, 3-3 and (*b*) in the direction longitudinal to sections 1-1, 2-2, 3-3.

corresponds to the accepted fracture scheme of the over-columned plate [4] when it is designed using the yield line method.

In addition, it should be noted that the plate works in two directions (figure 16), that is, the concrete of the compressed zone undergoes flat biaxial compression. This aspect is not fully taken into account in the calculations of its bearing capacity. Taking into account the actual stress-strain state of the over-columned plate of the precast flat plate floor system will make using principal reinforcement more economical to ensure the strength of the floor structure.

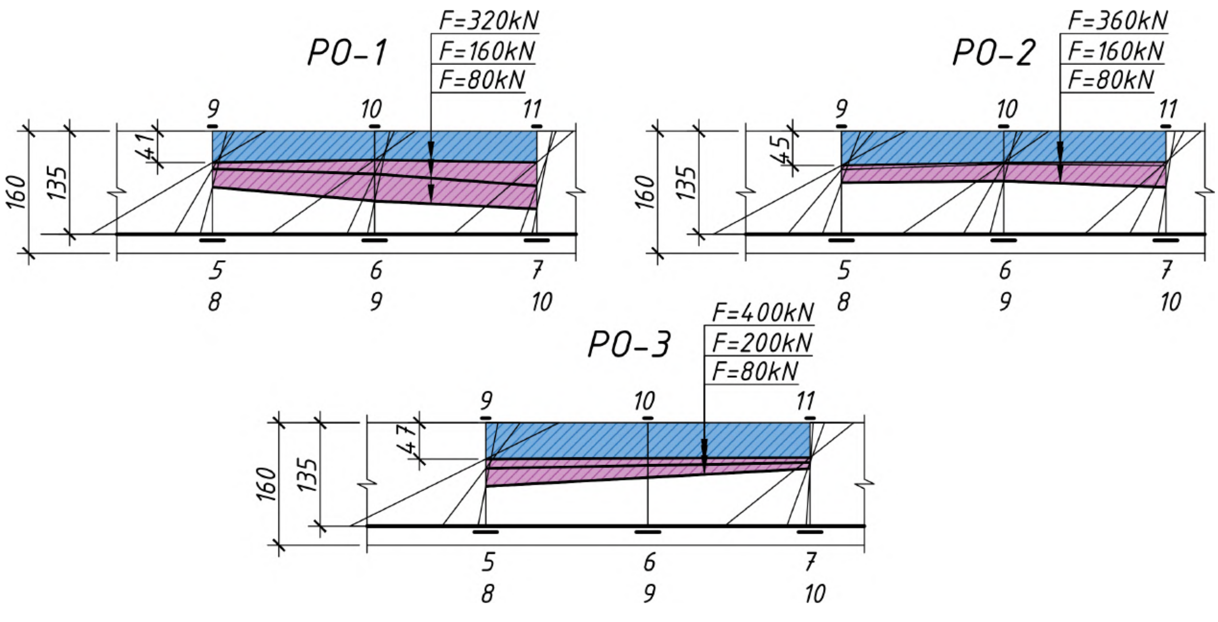


Figure 17. Change in the position of the neutral axis in the diagonal direction of the over-columned plates during loading.

One of the tasks set during the experiment was the task of investigating the change in the position of the neutral axis during the loading of the over-columned plate. This became possible thanks to the graphs in figure 17. To plot the graphs of the neutral axis position changing in the diagonal direction of the plate, the material strains plots were used based on the values of the data from the strain gauges.

As can be seen from figure 17, as the load increased, the compressed zone of concrete decreased, and the neutral axis moved up parallel to the most compressed face. This process occurred most intensively up to the value of the external load of 160 kN ($0.3F_{Rd}$), with a further increase in the load, it significantly slowed down, and after reaching the value of 280 kN ($0.5F_{Rd}$), it almost stopped. Based on the above, it can be concluded that the values of the neutral axis depth obtained from the experiment at loads of $0.55F_{Rd}$, $0.6F_{Rd}$ and $0.7F_{Rd}$ (figure 17) for PO-1, PO-2 and PO-3 plates, respectively, are quite close to the value of the neutral axis depth at the time of failure. At the same time, it should be noted that according to the calculation by the yield line method according to [4], the design neutral axis depth at destruction is $x = 43$ mm.

5. Conclusions

As a result of conducting experimental tests of full-scale samples of the over-columned plates of precast building frames, the following are established:

1. The scheme of supporting and loading of experimental over-columned floor plates during testing is adopted as close as possible to the actual plate operation scheme as part of a precast flat plate floor system during operation.
2. The average value of deflection l/200 is achieved under a load of $0.5F_{Rd}$, where $F_{Rd} = 580$ kN is the design value of the destructive load, calculated by the yield line method for the over-columned plate according to [4].
3. From the very beginning of the experiment, during the loading of the test samples, the maximum deformations of the reinforcement were observed along the characteristic lines located along the diagonal cracking lines of the over-columned plates.
4. It has been experimentally confirmed that the over-columned plate under the ultimate load is divided into four discs due to the formation of diagonal yield lines, which corresponds to the fracture pattern of the plate obtained by the yield line method according to [4].
5. The plate works in two directions, that is, the concrete of the compressed zone is subjected to flat biaxial compression. This aspect is not taken into account at the moment in the calculations of its carrying capacity. Taking into account the actual stress-strain state of the over-columned plate of the precast building frame will make using principal reinforcement more economical to ensure the strength of the floor structure.
6. The neutral axis depth decreases over the entire load period in all test samples of full-scale floor plates. When the load increases above 280 kN ($0.5F_{Rd}$), the decrease in the neutral axis depth is insignificant. Comparison of the estimated neutral axis depth at the moment of destruction by yield line method [4] $x_{teor} = 43$ mm with experimental data at loads of $0.55F_{Rd}$ (PO-1) $x_1 = 41$ mm; $0.6F_{Rd}$ (PO-2) $x_2 = 45$ mm; and $0.7F_{Rd}$ (PO-3) $x_3 = 47$ mm indicates their convergence.

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Vegetation zone segmentation in multispectral imagery

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Abstract. In the paper showing A U-Net-type convolutional neural network proposed for vegetation segmentation in multispectral imagery. The architecture of this network has modified and expanded to achieve better results with a smaller training dataset.The use of the network has made it possible to improve the solution to the problem of accurately identifying objects from the background based on existing information without the use of additional means of obtaining data. The processing of images of a corresponding nature is shown for 4-channel multispectral satellite images using a U-Net-shaped network trained on aerial images. Preprocessing showed the need to take into account the image formation model and perform post-training of the network based on the obtained data. A comparison conducted between the results of vegetation zone delineation in multispectral images using a convolutional neural network with a modified U-Net-like architecture and the Normalized Difference Vegetation Index (NDVI). The NDVI vegetation index uses data from various spectral channels and calculated as the ratio between intensities in the red and near-infrared channels of multispectral imagery, displayed as a number from -1 to +1, where a higher index value signifies denser green vegetation. Shown that for acceptable results, it is enough to use 4-channel images (NIR+RGB). The simulation performed in the MATLAB system.

1. Introduction

Semantic segmentation of images using convolutional neural networks allows for the assessment of vegetation areas in multispectral images with high resolution. To improve classification accuracy, multispectral images utilized, providing additional information for each pixel by supplementing color images with near-infrared channels. These channels contribute to clearer class separation and aid in distinguishing classes with similar visual characteristics, such as assigning a specific green pixel to classes like grass, shrubs, or trees.

The issue of the versatility of the models used is practically important. This paper shows the possibility of using U-Net-shaped architecture network, which is trained on a dataset with aerial images, to find vegetation zones in satellite images.

For the validation of results obtained through semantic segmentation, it is essential to obtain a reliable assessment of vegetation cover area independently. To achieve this, the Normalized Difference Vegetation Index (NDVI) proposed as a suitable metric [1]. NDVI is a simple quantitative indicator of the amount of photosynthetically active biomass, commonly referred to as a vegetation index.

The aim of the article it's to consider the implementation of semantic segmentation of a 4-channel multispectral image using a U-Net-shaped network and to assess the quality of segmentation of the vegetation zone using the calculation of the normalized differential vegetation index NDVI.

2. Related work

Numerous modifications of the basic algorithm for calculating NDVI have been developed to reduce the impact of various distortion factors, such as atmospheric aerosol absorption (Atmospheric-Resistant Vegetation Index, ARVI) and reflection from the soil surface (Soil Adjusted Vegetation Index, SAVI), etc. To calculate these indices, formulas are used that consider the relationship between the reflectance properties of various natural objects and vegetation in spectral ranges other than red and infrared, which makes their use more difficult. There are also indices that are based on NDVI and simultaneously correct for several distorting factors, for example, the Enhanced Vegetation Index (EVI) [2, 3].

As mentioned in original paper [4], the main idea of the U-Net architecture is to supplement a conventional convolutional network with a symmetrical part, where the pooling operations (dimensionality reduction) of objects are accordingly replaced by dimensionality increment operators that allow increasing the resolution of the output. In the part in which there is an increase in dimensionality, there are many feature channels that allow the network to spread contextual information to layers of higher resolution. Therefore, the part in which the expansion occurs is symmetrical to the part of the contraction, this gives a U-shaped architecture. Such a network uses only convolutions without any fully connected layers. To predict the value of pixels within an image area, the missing context is extrapolated by additional processing (which looks like a reflection from the point of view of network symmetry) of the input image. This tiling strategy is important for applying the network to large images, as otherwise the resolution will be limited.

The classic network architecture is shown in figure 1. It consists of two parts: compressive (left) and expanding (right), which give it its characteristic U-shape. The compression part follows a typical convolutional network architecture and consists of multiple convolutional layers with 3×3 cores, each followed by a ReLU activation layer (rectified linear unit) and pooling with a maximum function in increments of 2 to reduce the sample.

At each step of sampling, the number of functional features is doubled. Each step of the extension consists of a feature map oversample, followed by a 2×2 convolution that halves the number of features, a merge with a correspondingly cropped feature map from the compression portion, and two 3×3 convolutions, each accompanied by a ReLU. Cropping is necessary because of the loss of boundary pixels in each convolution.

On the final layer, convolution 1×1 is used to map each 64-component feature vector to a given number of classes. In total, the classical U-Net network has 23 convolutional layers [4].

Xie, Sha and Yu [5] discusses various methods for obtaining information about vegetation from remote sensing data, using color and texture information to interpret the images.

Wäldchen and Mäder [6] is one of the first systematic reviews of the literature, where, based on research published in 2005–2015, the results of computer vision studies for the identification of plant species were analyzed and compared.

The use of Convolutional Neural Networks (CNN) to automatically detect and map vegetation

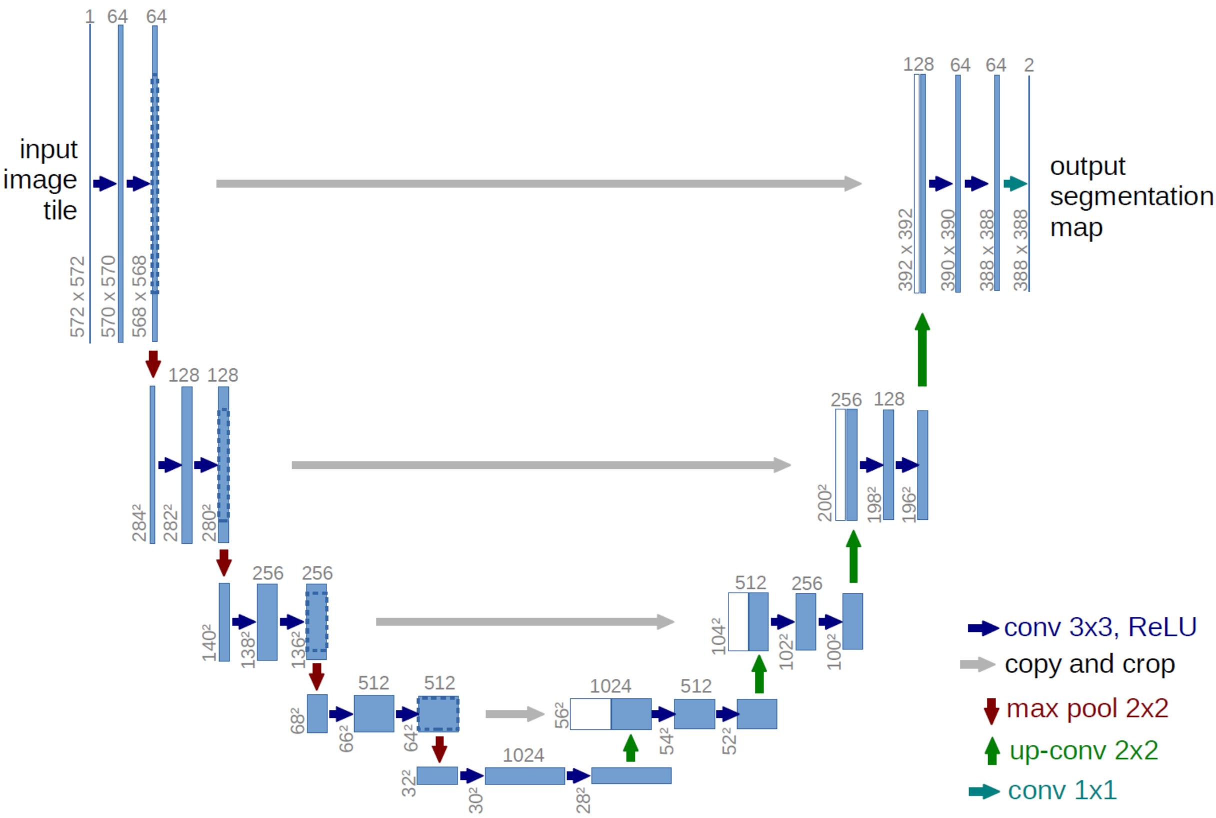

Figure 1. The architecture of the classic U-Net network [4].

using Google Earth imagery is described in [7], where the images are cut into several parts to improve the accuracy and performance of the model.

The effect of the number of channels on segmentation results was also investigated and it was found that the use of other than standard channels in the visible the additional near-infrared (NIR) band improves segmentation accuracy [8].

Kemker, Salvaggio and Kanan [9] explores the application of convolutional deep learning neural networks for semantic segmentation of multispectral view images.

3. Results

In this paper, we propose expanding the number of layers in the U-Net network from 42 to 58, while maintaining the same architecture described in [9]. This modification enables achieving satisfactory results for 4-channel (NIR+RGB) images, instead of requiring 6-channel (3 NIR + RGB) images. A complete list of layers of the proposed convolutional network is given in table 1.

Given that the primary objective is vegetation detection, segmentation into 4 classes is employed instead of 18 as mentioned in [9]:

1) water;
2) vegetation;
3) soil;
4) other.

Table 1: List of layers of the proposed U-Net-like convolutions network.

#	MATLAB notation	Layer name	Description
1	'ImageInputLayer'	Image Input	256×256×4 images with 'zerocenter' normalization
2	'Encoder-Section-1-Conv-1'	Convolution	64 3×3×4 convolutions with stride [1 1] and padding [1 1 1 1]
3	'Encoder-Section-1-ReLU-1'	Reread	Reread
4	'Encoder-Section-1-Conv-2'	Convolution	64 3×3×64 convolutions with stride [1 1] and padding [1 1 1 1]
5	'Encoder-Section-1-ReLU-2'	Reread	Reread
6	'Encoder-Section-1-MaxPool'	Max Pooling	2×2 max pooling with stride [2 2] and padding [0 0 0 0]
7	'Encoder-Section-2-Conv-1'	Convolution	128 3×3×64 convolutions with stride [1 1] and padding [1 1 1 1]
8	'Encoder-Section-2-ReLU-1'	Reread	Reread
9	'Encoder-Section-2-Conv-2'	Convolution	128 3×3×128 convolutions with stride [1 1] and padding [1 1 1 1]
10	'Encoder-Section-2-ReLU-2'	Reread	Reread
11	'Encoder-Section-2-MaxPool'	Max Pooling	2×2 max pooling with stride [2 2] and padding [0 0 0 0]
12	'Encoder-Section-3-Conv-1'	Convolution	256 3×3×128 convolutions with stride [1 1] and padding [1 1 1 1]
13	'Encoder-Section-3-ReLU-1'	Reread	Reread
14	'Encoder-Section-3-Conv-2'	Convolution	256 3×3×256 convolutions with stride [1 1] and padding [1 1 1 1]
15	'Encoder-Section-3-ReLU-2'	Reread	Reread
16	'Encoder-Section-3-MaxPool'	Max Pooling	2×2 max pooling with stride [2 2] and padding [0 0 0 0]
17	'Encoder-Section-4-Conv-1'	Convolution	512 3×3×256 convolutions with stride [1 1] and padding [1 1 1 1]
18	'Encoder-Section-4-ReLU-1'	Reread	Reread
19	'Encoder-Section-4-Conv-2'	Convolution	512 3×3×512 convolutions with stride [1 1] and padding [1 1 1 1]
20	'Encoder-Section-4-ReLU-2'	Reread	Reread
21	'Encoder-Section-4-DropOut'	Dropout	50% dropout
22	'Encoder-Section-4-MaxPool'	Max Pooling	2×2 max pooling with stride [2 2] and padding [0 0 0 0]
23	'Mid-Conv-1'	Convolution	1024 3×3×512 convolutions with stride[1 1] and padding [1 1 1 1]
24	'Mid-ReLU-1'	Reread	Reread
25	'Mid-Conv-2'	Convolution	1024 3×3×1024 convolutions with stride [1 1] and padding [1 1 1 1]
26	'Mid-ReLU-2'	Reread	Reread
27	'Mid-DropOut'	Dropout	50% dropout
28	'Decoder-Section-1-UpConv'	Transposed Convolution	512 2×2×1024 transposed convolutions with stride [2 2] and cropping [0 0 0 0]

Continued on next page

Table 1 – continued from previous page

#	MATLAB Notation	Layer name	Description
29	'Decoder-Section-1-UpReLU'	Reread	Reread
30	'Ponderr-Section-1-DepthConcatenation'	Depth concatenation	Depth concatenation of 2 inputs
31	'Decoder-Section-1-Conv-1'	Convolution	512 3×3×1024 convolutions with stride [1 1] and padding [1 1 1 1]
32	'Decoder-Section-1-ReLU-1'	Reread	Reread
33	'Decoder-Section-1-Conv-2'	Convolution	512 3×3×512 convolutions with stride [1 1] and padding [1 1 1 1]
34	'Decoder-Section-1-ReLU-2'	Reread	Reread
35	'Decoder-Section-2-UpConv'	Transposed Convolution	256 2×2×512 transposed convolutions with stride [2 2] and cropping [0 0 0 0]
36	'Decoder-Section-2-UpReLU'	Reread	Reread
37	'Ponderr-Section-2-DepthConcatenation'	Depth concatenation	Depth concatenation of 2 inputs
38	'Decoder-Section-2-Conv-1'	Convolution	256 3×3×512 convolutions with stride [1 1] and padding [1 1 1 1]
39	'Decoder-Section-2-ReLU-1'	Reread	Reread
40	'Decoder-Section-2-Conv-2'	Convolution	256 3×3×256 convolutions with stride [1 1] and padding [1 1 1 1]
41	'Decoder-Section-2-ReLU-2'	Reread	Reread
42	'Decoder-Section-3-UpConv'	Transposed Convolution	128 2×2×256 transposed convolutions with stride [2 2] and cropping [0 0 0 0]
43	'Decoder-Section-3-UpReLU'	Reread	Reread
44	'Ponderr-Section-3-DepthConcatenation'	Depth concatenation	Depth concatenation of 2 inputs
45	'Decoder-Section-3-Conv-1'	Convolution	128 3×3×256 convolutions with stride [1 1] and padding [1 1 1 1]
46	'Decoder-Section-3-ReLU-1'	Reread	Reread
47	'Decoder-Section-3-Conv-2'	Convolution	128 3×3×128 convolutions with stride [1 1] and padding [1 1 1 1]
48	'Decoder-Section-3-ReLU-2'	Reread	Reread
49	'Decoder-Section-4-UpConv'	Transposed Convolution	64 2×2×128 transposed convolutions with stride [2 2] and cropping [0 0 0 0]
50	'Decoder-Section-4-UpReLU'	Reread	Reread
51	'Ponderr-Section-4-DepthConcatenation'	Depth concatenation	Depth concatenation of 2 inputs
52	'Decoder-Section-4-Conv-1'	Convolution	64 3×3×128 convolutions with stride [1 1] and padding [1 1 1 1]
53	'Decoder-Section-4-ReLU-1'	Reread	Reread
54	'Decoder-Section-4-Conv-2'	Convolution	3×3×64 convolutions with stride [1 1] and padding [1 1 1 1]
55	'Decoder-Section-4-ReLU-2'	Reread	Reread

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Table 1 – continued from previous page

#	MATLAB Notation	Layer name	Description
56	'Final-ConvolutionLayer'	Convolution	1×1×64 convolutions with stride [1 1] and padding [0 0 0 0]
57	'Softmax-Layer'	Softmax	Softmax
58	'Segmentation-Layer'	Pixel Classification Layer	Cross-entropy loss

The **Image Input Layer** splits the original image into 256×256×4 (for 4-channel viewports).

Convolution Layers perform convolutions with 3×3 cores for each of the 4 channels, offset step stride=[1 1], completion 0 to prevent edge effects.

ReLU Activation Layers perform a threshold operation on each element, setting the value to zero for negative values.

Max Pooling Reduction Layers reduce dimensionality by dividing into rectangular regions, with the original elements being the maxima for each region.

Dropout Reduction Layers set the output elements to 0 with a given probability.

Transposed Convolution Layers perform convolutions with transposed kernels (sometimes incorrectly referred to as convolution wrap layers).

Depth Concatenation layers combine inputs along the third dimension.

Softmax Activation layers apply to the inputs a *Softmax* function defined as:

$$sofmaxx = \frac{e^x}{\sum e^x} \tag{1}$$

The output **Pixel Classification** Layer makes a final classification of each pixel, minimizing the given loss function. In this paper, the *Cross-entropy* loss function is used as a loss function, which is a measure of error between two continuous random variables. For the forecasted values Y and target values T the weighted cross-entropy is calculated as:

$$L = \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} w_k T_{nk} \log Y_{nk} \tag{2}$$

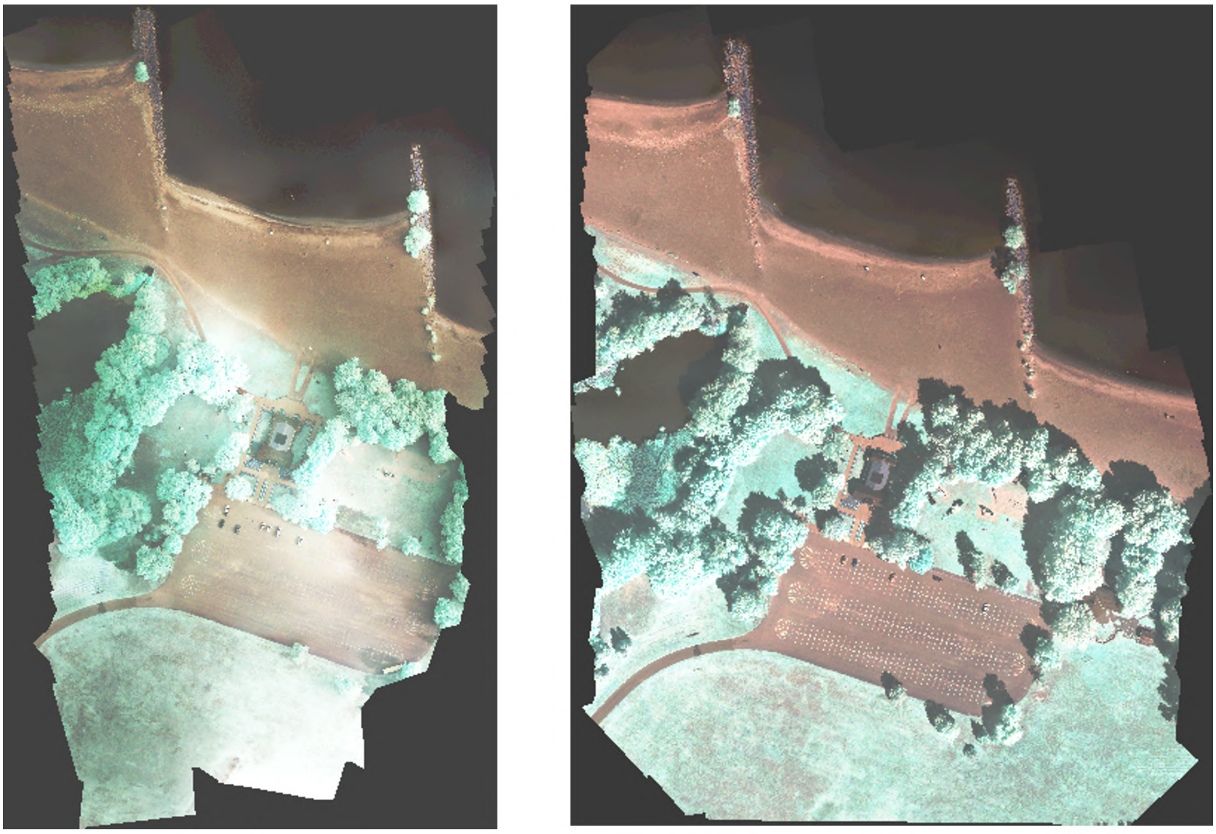
where N is the number of observations, K is the number of classes, and wk is the vector of weighting coefficients for each class k.

To facilitate comparison with the findings in [9], we utilized the identical aerial images sourced from the Hamlin Beach State Park dataset [10] for both training and testing purposes (figure 2).

The proposed network trained using the Stochastic Gradient Descent with Momentum Optimization (SGDM) algorithm. SGDM parameters were set using the *trainingOptions* function (Deep Learning Toolbox).

```
initialLearningRate = 0.05;
maxEpochs = 150;
minibatchSize = 16;
L2reg = 0.0001;

options = trainingOptions(...
'sgdm', ...
'InitialLearnRate', initialLearningRate, ...
'Momentum', 0.9, ...
'L2Regularization', l2reg, ...
```



a) b)

Figure 2. Images from the Hamlin Beach State Park dataset [10]: a) the image used for training; b) the image used for validation.

'MaxEpochs', MaxEpochs, ...
'MiniBatchSize', minibatchSize, ...
'LearnRateSchedule', 'piecewise', ...
'Shuffle', 'every-epoch', ...
'GradientThresholdMethod', 'l2norm', ...
'GradientThreshold', 0.05, ...
'Plots', 'training-progress', ...
'VerboseFrequency', 20);

Since the result of segmentation is noisy, it is advisable to perform post-processing using the median filtering function with a window of size [15,15]. The optimal size of the filtering window depends on the size of the characteristic noise elements, which in turn will depend on the image parameters.

The main indicators of segmentation quality are accuracy, intersection to union ratio (IoU) and assessment of the correspondence of the boundary contour F1 (BF).

For each class, Accuracy is the ratio of correctly classified pixels to the total number of pixels in that class, according to true values, i.e.:

$$Accuracy = TP/(TP + FN) \tag{3}$$

where TP is the number of true-positive classifications, and FN is the number of false-negative classifications.

The intersection to union ratio (IoU), also known as the Jacquard similarity coefficient, is the most used metric. For each class, IoU is the ratio of correctly classified pixels to the total number of true-positive and predictable pixels in that class. In other words

$$IoU = TP/(TP + FP + FN) \tag{4}$$

where FP are false-positive classifications.

The F1 (BF) boundary contour conformity assessment indicates the extent to which the intended boundary of each class is consistent with the true boundary. The BF score is used when there is a need for an indicator to generally be better related to a person's qualitative score than an IoU score.

Now let's define the standard segmentation quality metrics:

1. **Global Accuracy** is the ratio of correctly classified pixels, regardless of class, to the total number of pixels. It is used in cases where a quick and inexpensive estimate of the percentage of correctly classified pixels is required.
2. **Mean** Accuracy is the average of the Accuracy score for all classes in all images, with Accuracy indicating the percentage of correctly identified pixels for each class. Used when you want to read how correctly each class defines pixels.
3. **Mean IoU (average intersection to union ratio) is the average IoU value for all classes in all images.**
4. **Weighted** IoU (weighted intersection to union ratio) is the average IoU value of each class, weighted by the number of pixels in that class. This metric is used if images have disproportionately large classes to reduce the impact of small-class errors on the overall quality score.
5. Mean BFScore is the average of the BFScore score for all classes in all images.

Comparative results of segmentation quality for 6-channel and 4-channel images are shown in table 2.

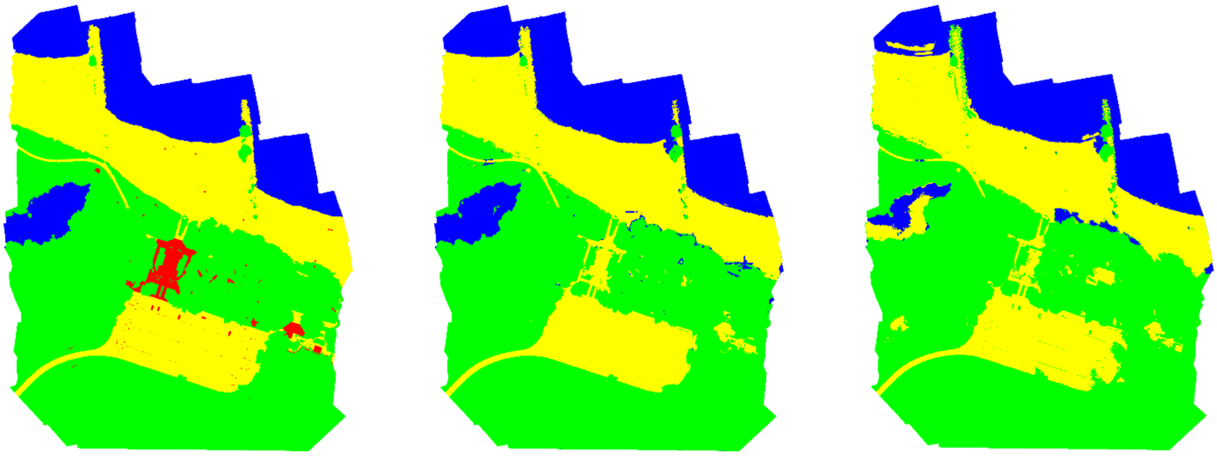
Table 2. Results of segmentation quality comparison.

	Global accuracy	**Mean accuracy**	**Mean IoU**	**Weighted IoU**	**Mean BFScore**
6-channel images	0.96567	0.7363	0.70823	0.93358	0.86183
4-channel images	0.92792	0.69431	0.6484	0.86541	0.76955

The results of segmentation of 4-channel images are expected to be slightly worse than the results of 6-channel images but are quite acceptable for vegetation zone selection tasks.

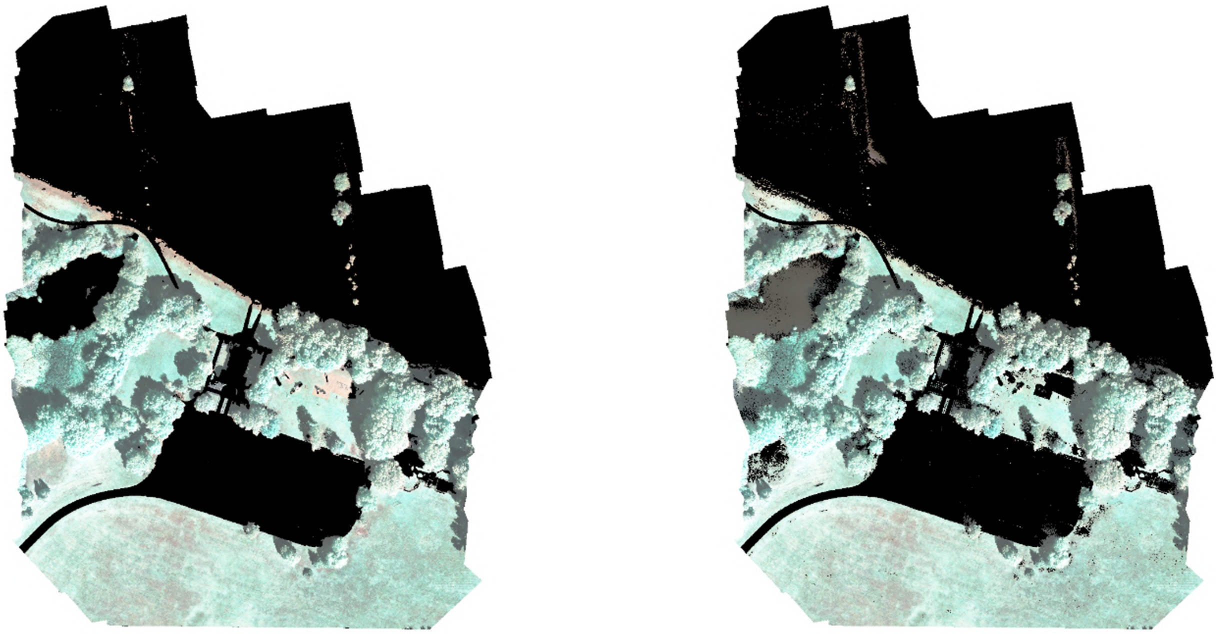
Thus, an additional check is to determine the proportion of the area occupied by vegetation cover. The direct method of determining this number is to calculate the relative area of class corresponding to vegetation.

vegetationClassIds = uint8(2);
vegetationPixels
= ismember(segmentedImage(:),vegetationClassIds);
validPixels = (segmentedImage =0);



a) b) c)

Figure 3. The results of the semantic segmentation: a) ground truth (derived from work [9], combining 18 classes into 4); b) aerial 6-channel image; c) aerial 4-channel image.



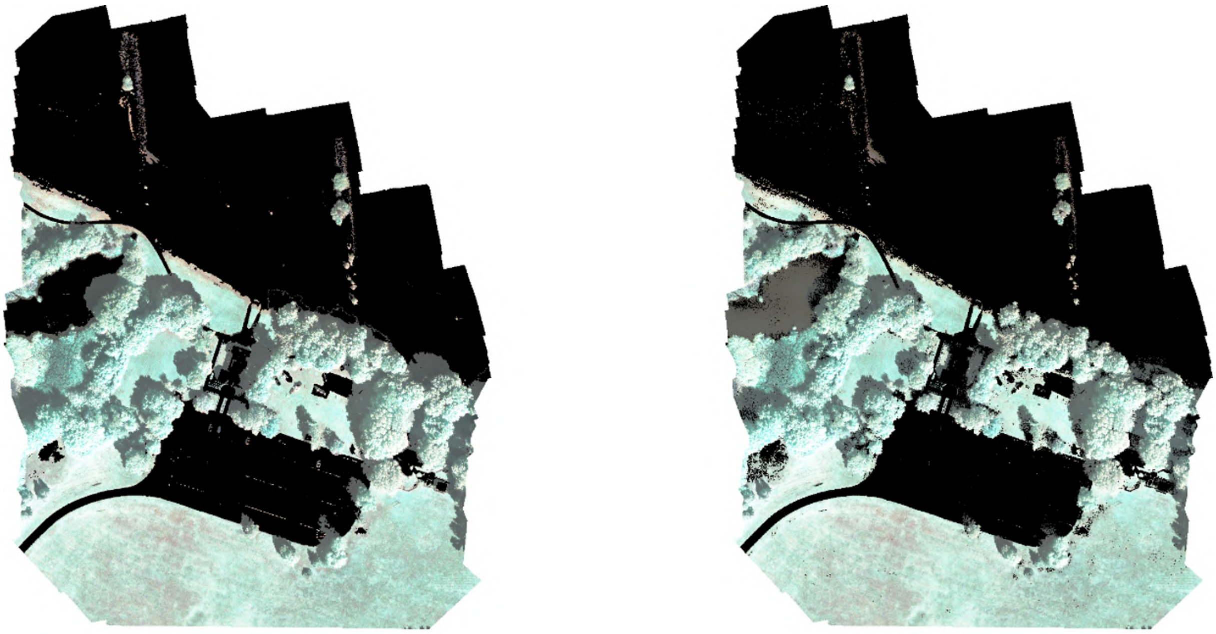
a) b)

Figure 4. The result of the selection of vegetation zones for a 6-channel test image: a) using vegetation class; b) using vegetation index.

```
numVegetationPixels = sum(vegetationPixels(:));
numValidPixels = sum(validPixels(:));

percentVegetationCover = (numVegetationPixels / numValidPixels;
```

Another way is through the determination of the vegetation index with its subsequent



a) b)

Figure 5. The result of the selection of vegetation zones for a 4-channel test image: a) using vegetation class; b) using binarized NDVI.

Figure 6. Map of the area with marked areas of interest.

binarization. Recall that the value of the $NDVI$ vegetation index is calculated using the formula:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{5}$$

where NIR and R are the near-infrared (800 nm) and red (670 nm) channels of the multispectral image, respectively.

To assess the proportion of area covered by vegetation, we binarized the obtained values of NDVI by applying the Otsu method. This yielded a vegetation cover area fraction of **0.5095** both for 6-channel and for 4-channel images (the values are same because it used the same red

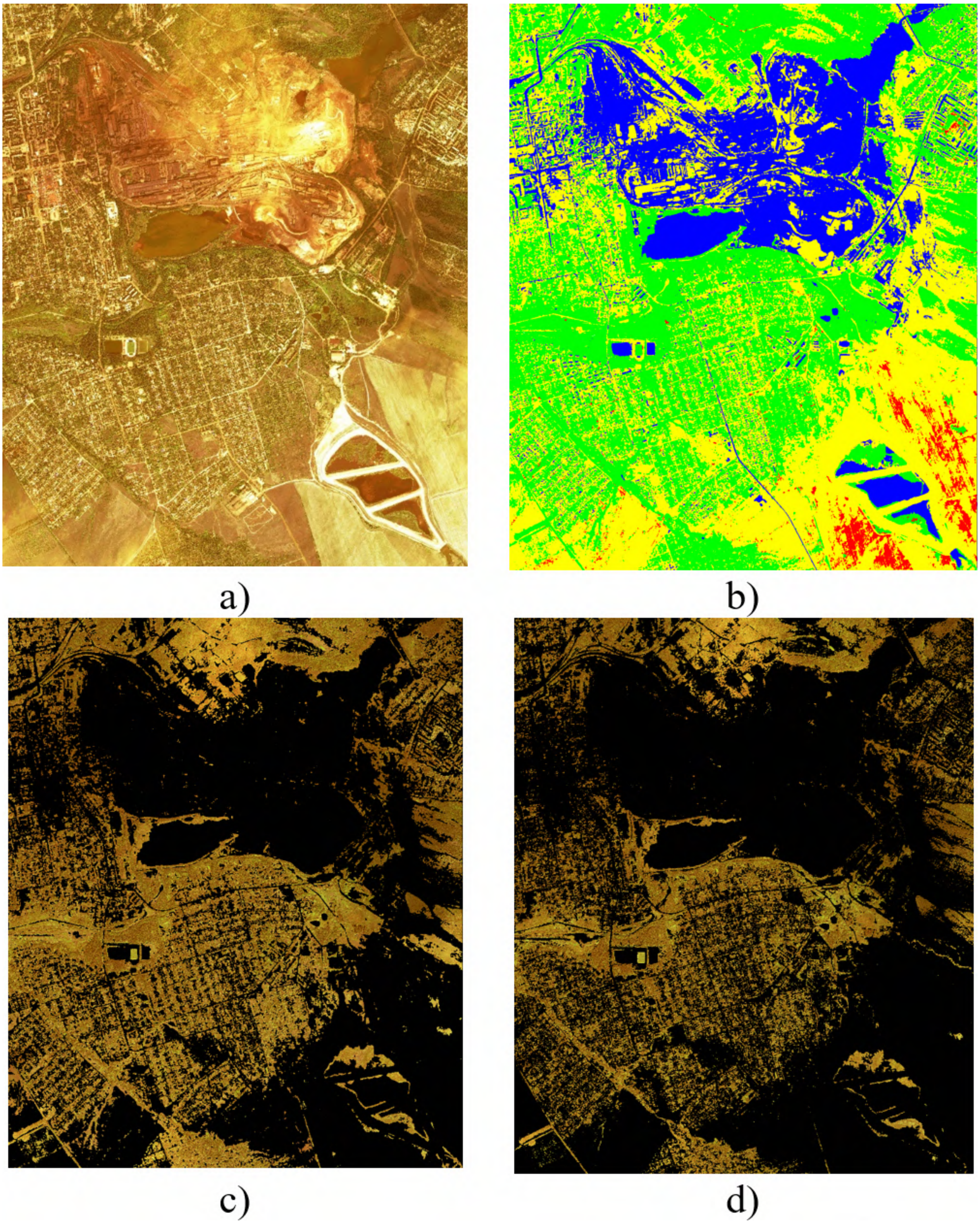


Figure 7. Results of processing for "Fragment 1": a) the original image; b) labeled image; c) selection of vegetation zones using vegetation class; d) selection of vegetation zones using binarized NDVI.

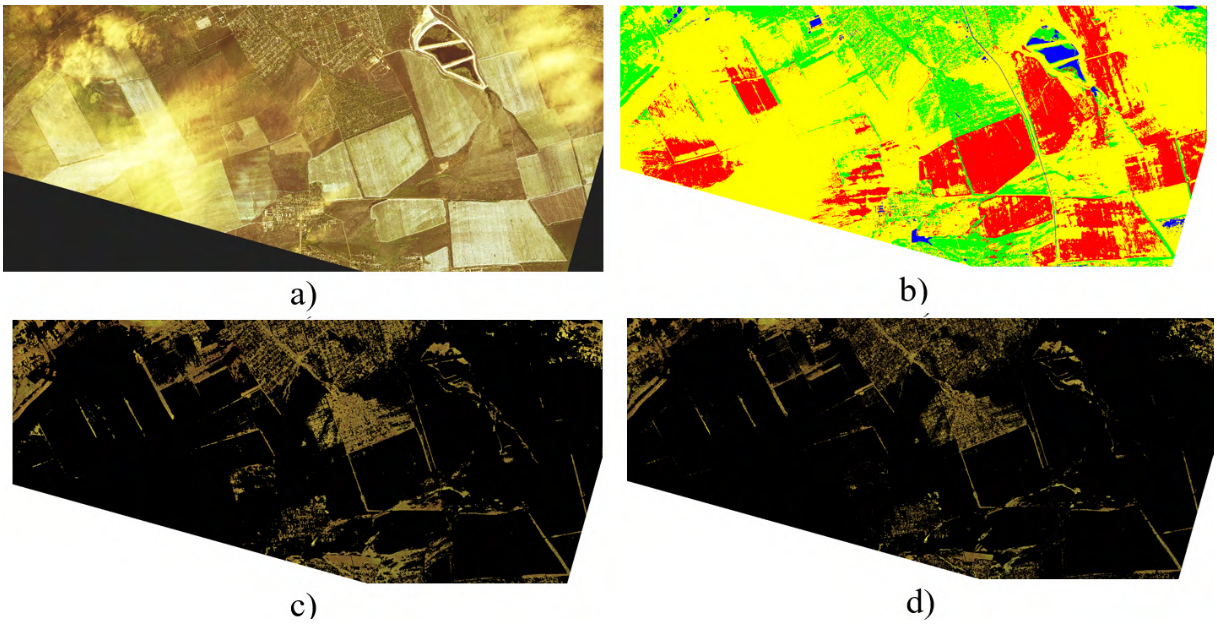


Figure 8. Results of processing for "Fragment 2": a) the original image; b) labeled image; c) selection of vegetation zones using vegetation class; d) selection of vegetation zones using binarized NDVI.

and NIR channels for both cases).

These values align closely with previously calculated values of **0.5185** and **0.5356** for the relative vegetation area, validating the accuracy of semantic segmentation via NDVI method. In the figure 3, figure 4 and figure 5 illustrate the results of vegetation zone selection for the test image, corresponding to 6-channel and 4-channel processing, respectively.

For additional experiments, 4-channel satellite images of the region near Yenakiieve, Donetsk region, denoted as "Fragment 1" and "Fragment 2" (refer to figure 6), were employed.

Note that the image is fed to the network input without any pre-processing, so as not to change its statistics in relation to the images from the dataset that were used for post-training of the network.

In the figure 7 and figure 8 shows the results of processing for "Fragment 1" and "Fragment 2" respectively.

4. Conclusions

This paper demonstrates the process of semantic segmentation using a U-Net-like network, illustrated through the processing of both 6-channel aerial images and 4-channel multispectral satellite images. While the segmentation results of 4-channel images are anticipated to be slightly inferior to those of 6-channel images, they are deemed acceptable for vegetation zone selection tasks. Moreover, utilizing 4-channel images notably reduces processing time. Of particular interest is the ability to train the model with aerial images dataset, allowing its application to satellite images. The quality of vegetation zone segmentation was evaluated in comparison with the normalized differential vegetation index (NDVI). Through analyzing the results obtained, a strong correspondence was observed between the outcomes of semantic segmentation via neural network and NDVI usage.

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Calculation of round foundation slabs subjected to non-uniform base deformation under complex loads

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Abstract. New patterns of determining internal forces for possible conditions of elements of the first and second categories of reinforced concrete slabs subjected to complex loads are established. The introduction into the calculation of a function characterizing the degree of reduction of weakened bases' properties in order to determine the stiffness coefficient with load relief makes it possible to take into account the conditions of contact interaction between the slab and the non-uniformly deformed base. A program is developed to consider the load history of elements using nonlinear diagrams in the whole range of force and deformation effects. The results of simulating the slab's operation on a non-uniformly deformed base under complex loads are obtained. The developed program allows determining the maximum load on the structure with known values of expected deformation effects and solving the opposite problem, i.e. determining the maximum deformation effects with constant external loads caused by structures.

1. Introduction

Slab foundations occupy a significant place among building structures and are widely used in industrial and civil construction. Monolithic reinforced concrete slab foundations of rectangular, polygonal, and round shape are used in construction on natural foundations. They are particularly widely used in complex engineering and geological conditions in the construction of high-rise buildings of various functional purposes, as well as industrial structures such as silos, elevators, flue pipes, etc. The joint operation of these structures with the ground base is conditioned by many factors that should be taken into account when laying foundations, increasing load during construction of buildings and structures and by deformation influences from the base during the operation period [1–4]. Thus, the technical and economic parameters of slab foundations can be determined taking into account their actual operation under real operating conditions, such as loading modes, the nature of force and deformation effects, peculiarities of development of irreversible deformations, settlement of structures, the sequence of formation, opening and closing of cracks, etc.

Their calculation, performed in a linear setting, is associated with the difficulty of obtaining reliable results due to the complexity of the structure of resolving equations, as well as a large number of unknown parameters.

The linear calculation theory with the solution of new problems posed by the construction practice is not universally applicable. This is especially true for calculations of structures designed for complex engineering and geological conditions (swelling, structurally unstable soils, underworked, karsted and landslide areas).

Although the basic patterns of characteristic manifestations in these areas are known, taking into account all the features of the real soil mass is a complex task of soil mechanics. The solution of this problem is possible with the use of numerical calculation methods implemented in simulation programmes [5–8].

By creating soil models, in which there are simultaneously zones of pre-limit and limit states, the non-linear nature of the "load-settling" relationship can be determined, as well as taking into account the variety of physical processes accompanying the deformation of this base.

The behaviour (deformation and depletion of load-bearing capacity) of rectangular and round foundation slabs on the uniformly deformed base has been sufficiently studied [9], but under conditions of non-uniform base deformations, this question still remains understudied, although the types and characteristics of the deformation are known and investigated.

At present, modern calculation methods for buildings and structures operating in complex soil conditions, and, first of all, foundation structures interacting with unevenly deformed base are being developed.

2. Research objectives

The research aims to substantiate and develop a method of calculating round foundation slabs interacting with the non-uniformly deformed base, taking into account inelastic deformations of reinforced concrete and soil under complex loading.

In order to achieve this goal, it is necessary to solve the following tasks:

- to perform an analysis of the available experimental data and theoretical generalizations to select the regularity of deformation of the reinforced concrete slab and the soil base under complex loading;
- to carry out complex experimental and theoretical studies of the stress-deformed state of round-shaped plates in their joint work with the deformable base;
- to develop static methods of calculating round foundation slabs with comprehensive consideration of non-linear and inelastic deformations of reinforced concrete and soil under complex load;
- to develop application programs to calculate round foundation slabs in a non-linear and non-elastic arrangement;
- to identify features and patterns of nonlinear-inelastic deformation of round foundation slabs and bases by simulating their work using the developed methods and calculation programs;
- to introduce the research results into design practice, construction and operation of buildings and structures operating under special conditions.

3. Results

Round foundation slabs are calculated for difficult soil conditions taking into account the infinite stiffness of the slabs. Design and construction practice indicates that, on the one hand, with high slab stiffness there are significant strength reserves, the use of which is hindered by the lack of uniform recommendations for rational slab foundation design. On the other hand, even with sufficient stiffness, the foundation slab bends and gets maximum deflection under load, especially in the non-linear stage of reinforced concrete work, when cracks and fracture lines are formed. It follows that the assumption of infinite stiffness does not reflect the actual work of the structure, and deformation (flexibility) of the slab should be considered in the calculation.

Consideration of non-linear deformation of materials that causes stress redistribution in both components of the foundation-base system makes the contact problem under conditions of non-uniform deformation of the foundation non-linear not only physically but also geometrically, because the locations of the base detachment from the foundation bed are unknown in advance.

Reinforced concrete is known to be an elastic material. If deformation reduces the value of the moment at a cross-section, the load relief curve does not coincide with the load curve. Therefore, slab stiffness should be determined considering the load history. Existing programs for calculating foundation slabs do not take into account specific features of deformation of reinforced concrete during load belief.

Deformations of the base not related to the load of the structure are reflected in the calculation diagram by the corresponding values of the vertical and horizontal shears of the base surface [10]. The calculation of slab foundations with respect to the action of non-uniform deformations of the foundations is performed by considering all possible deformations from the state of the foundation-base joint work, taking into account the most unfavorable combination of the effects.

The most unfavorable options for reactive pressures to be implemented can occur with the following deformation-force combinations (figure 1):

- curvature of the convex surface of the base and the external moment which is perpendicular to the curvature plane;
- curvature of the concave surface of the base and the external moment which is parallel to the curvature plane;
- a ledge or failure at the end of the base and the external moment which is perpendicular to the ledge line.

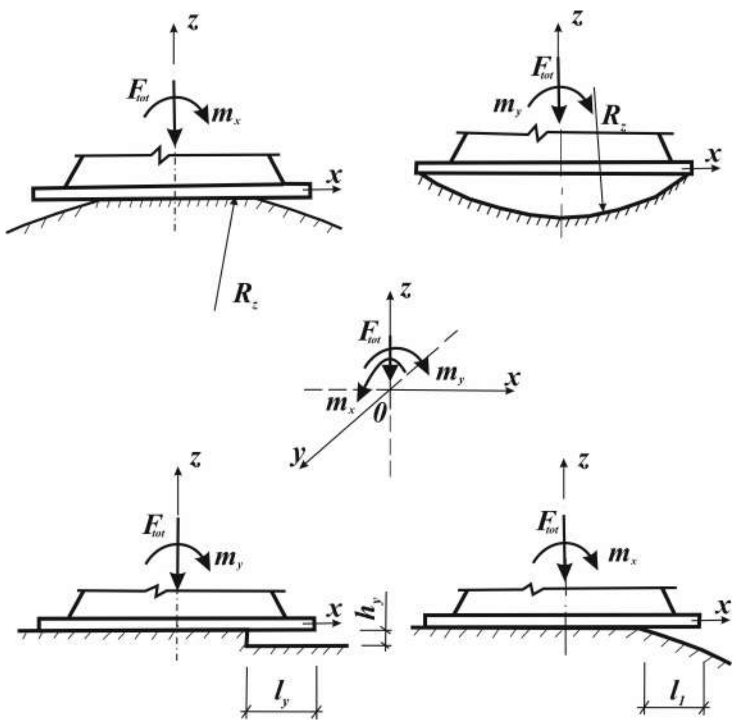

Figure 1. Unfavourable options of the combination of external structure-caused loads and base-caused deformation effects.

There is only one-way connection between the foundation slab and the base, i.e. the base is not capable of preventing the separation of the foundation from the soil, but only prevents the penetration of the slab [10–12].

Further deformation of the base changes physical and mechanical characteristics of the soil, the bearing capacity and the stiffness of the base are reduced [13]. At the same time, the soil deformation curve in the new state do not coincide with the first curve. Therefore, when solving the contact problem for these conditions, it is necessary to take into account the differences in the soil load curves for different points before and after the weakening of the base.

Describe an algorithm that takes into account nonlinear and inelastic properties of the base during complex loads, yet without considering specific features of reinforced concrete deformation [14–17]. In addition, reduction in mechanical properties of the base is considered only for settling soils [14, 16], while in underworking, for example, the change in the soil deformation diagram is neglected [17], although [18] notes that stiffness properties of the base are reduced.

Thus, analysis of existing researches on the behaviour of round foundation slabs interacting with the non-uniformly deformed base shows that there is not yet a generally accepted calculation method that allows simultaneous consideration of the features of deformation of reinforced concrete and soil at complex loading which occurs with additional (independent of external load) deformation of the base in buildings and structures.

The base model is selected according to the design values of contact pressures determined from the sum of the values of vertical load resistance at the interaction of the foundation with the deformed base and horizontal load resistance at the interaction of the slab with the non-deformed base. Frictional forces on the foundation bed due to horizontal deformation of the soil are believed not to affect the bending of the slab, and, therefore distribution of contact pressures [10, 19].

Foundation slab deformations caused by transverse loads and base settling have little effect on horizontal deformation forces. The forces in the foundation slab from vertical shears and horizontal deformations of the foundation are determined separately. At the same time, the forces caused by horizontal deformations are thought to be perceived by the bottom reinforcement.

Solving the problem of determining the load-bearing capacity of foundation slabs operating under non-uniform base deformations requires considering non-linear and inelastic deformations of reinforced concrete and soil. In addition, it is necessary to take into account geometric nonlinearity of the contact problem.

In the case of non-uniform base deformations, it is of practical importance to determine the maximum deformation effects on the slab foundations, i.e. the maximum values of deformation forces that the foundation slab can withstand under constant external loads caused by the structure.

Analysis of real conditions of structures interacting with the non-uniformly deformed base shows that to effectively design structures of foundation slabs in complex soil conditions, it is necessary to consider the following assumptions:

- the foundation slab has a finite stiffness, while the stiffness of each element of the slab depends on a reinforced concrete work stage;
- soils deform non-linearly, so stiffness characteristics of the base should be determined taking into account its interaction with the structure;
- additional deformation of the base occurs during structures' operation. It follows that it is necessary to consider the differences in deformation curves of reinforced concrete and soil during loading and load relief.

On the basis of these provisions, it is possible to correctly solve the following, not sufficiently researched, but important scientific and practical problems:

- specifying the general stress-deformed state picture of foundation slab designs operating under conditions of non-uniform deformation of the base;
- defining the effect of each type of base deformation on foundation slabs;
- determining limit deformation effects on the foundation slab under constant external loads caused by the structure;
- specifying the limit load (caused by the structure) on the foundation slab design, if the value of expected possible deformation effects is previously known.

The operation of round foundation slabs under non-uniform deformations of the base, taking into account deformation characteristics of reinforced concrete and soil, can be studied on mathematical models [13, 20, 21]. For this purpose, consider a round foundation slab under the influence of arbitrary normal to the median plane of the slab external load intensity $q\ (r, \varphi)$ and lying on the soil base, characterized by the stiffness coefficient $k_1(r,\ \varphi)$ (figure 2), where $r,\ \varphi$ are polar coordinates.

The slab has a finite stiffness, but large enough to ignore membrane forces acting on the foundation bed and having little effect on the overall slab operation, especially on its load-bearing capacity. The load from these forces is perceived only by the lower part of the cross-section, so they cannot exhaust the load-bearing capacity of the slab.

The behavior of a reinforced concrete foundation slab at any operation stage is described by systems of resolving equations, combining equilibrium, geometric and physical equations ones.

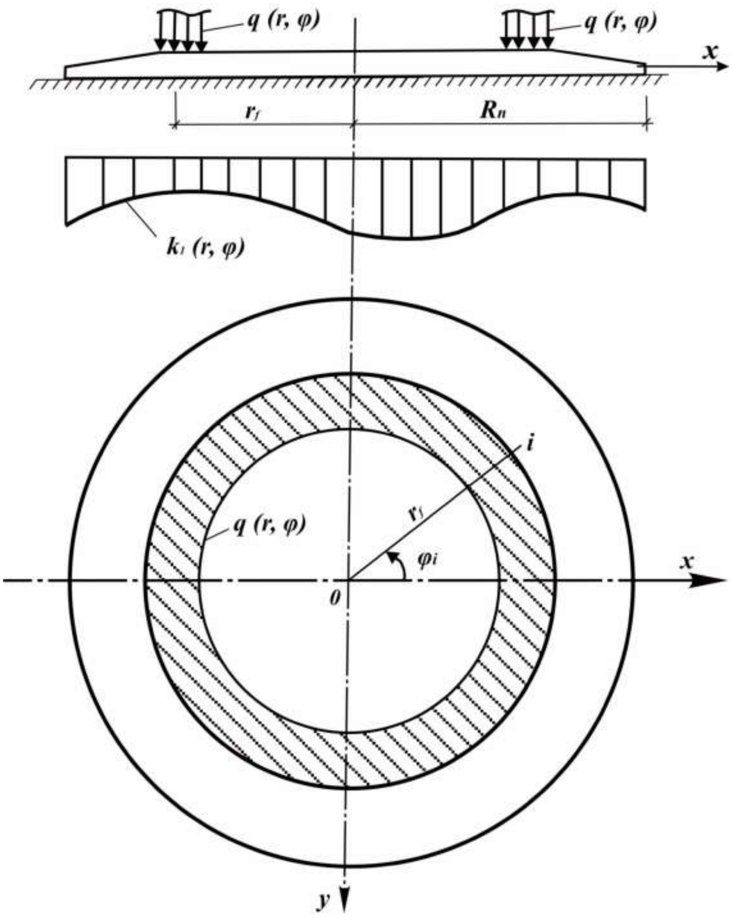

Figure 2. Round foundation slab on the soil base.

The calculation is made under various deformation conditions of the round foundation slab base with the following characteristics:

- geometric dimensions of the slab are shown in figure 3,a;
- curves of the coefficients of reinforcement of the lower and upper slab zones in the radial and annular directions are shown in figure 3,b;
- concrete is class C25/30; as working reinforcement is represented by class A400 steel, radial rods are A400 ∅ 28; ring rods are A400 ∅ 25.

The round foundation slab is reinforced according to the requirements [9, 22–25].

Consider first the operation of the foundation slab under normal soil conditions with the increased total vertical load F_{tot} caused by the structure. For calculation, the soil deformation diagram [17] is taken and the initial stiffness coefficient of the base is $k_i = 58.8\ MN/m^3$.

The simulation results (settling W, reactive pressures P, radial and annular moments M_r and M_φ, crack formation zones) at load F_{tot} equal to 200 MN, 300 MN, 375 MN, and 400 MN are shown in figure 4.

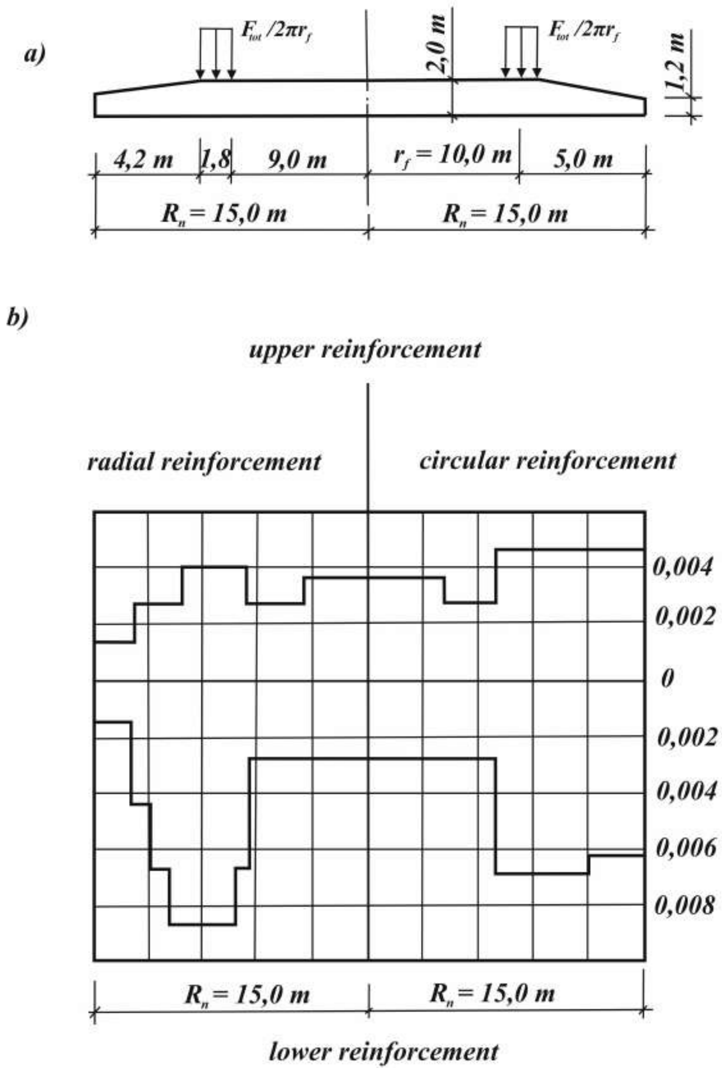

Figure 3. Characteristics of foundation slab: a) geometric dimensions; b) curves of reinforcement coefficients.

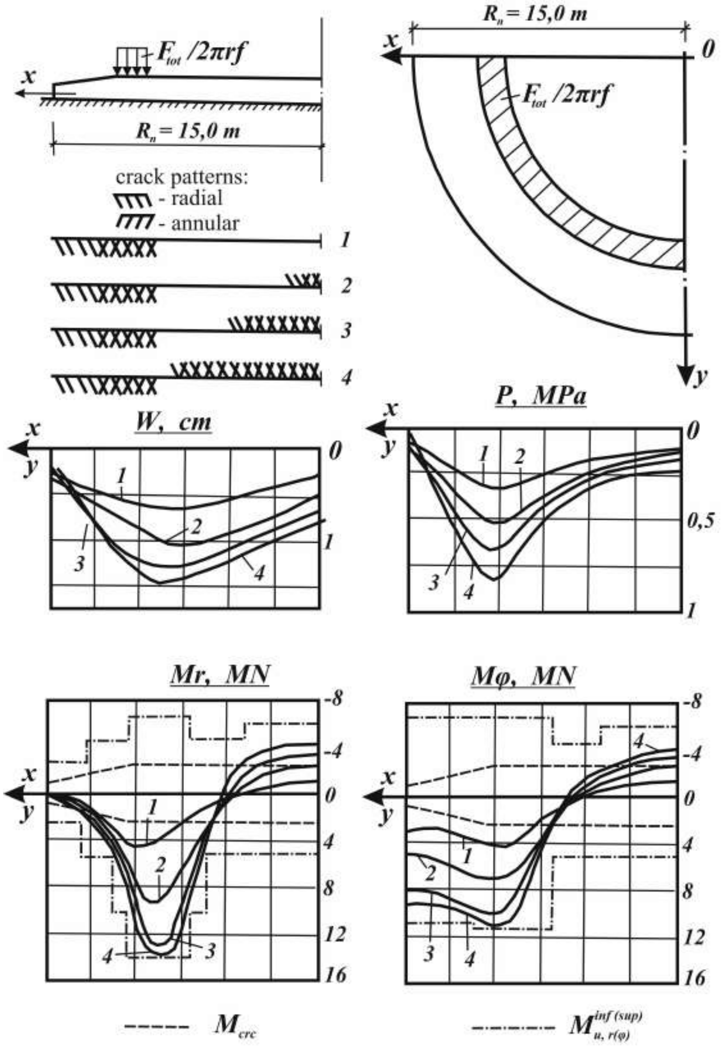

Figure 4. Calculation results under natural soil conditions with the vertical load F_{tot} equal to: 1 – 200 MN; 2 – 300 MN; 3 – 375 MN; 4 – 400 MN.

At $F_{tot} = 400\ MN$, plastic hinges form closed areas, annular and radial fracture lines divide the slab into several separate parts, and thus the load-bearing capacity of the foundation slab is exhausted.

The value $F_{tot,\ u} = 400\ MN$ is the limit load on a given slab under normal soil conditions.

3.1. Simulation of the curvature of the convex base surface

Now consider the behaviour of the round foundation slab with the curvature of the convex surface of the base along the axis Υ (i.e. $\upsilon\,(r,\,\varphi) = \upsilon\,(x)$, figure 5).

The characteristics of the slab are the same. It is subject to a total vertical load $F_{tot,\ 1} = 200\ MN$, which is twice as less than the limit load $F_{tot,\ u}$ ($n_R = F_{tot,u}/F_{tot,1} = 2,0$ is the factor of safety of the foundation slab under normal soil conditions).

It is necessary to determine the stress-deformed state of the round foundation slab when the curvature of the convex base surface is increased. The following values of the curvature radius R_z are used in simulation: 10000 m, 6000 m, 4000 m.

Reduced characteristics of the deformed base are determined according to [18] and [19,26–29].

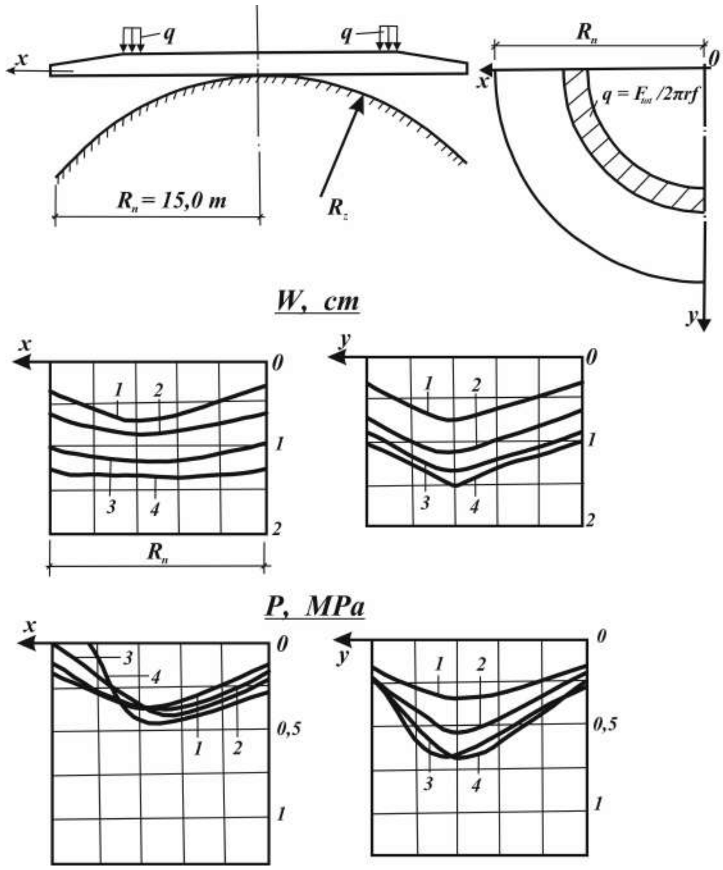

Figure 5. Settling W and contact pressures P along the central axes OX and OY under vertical load $F_{\text{tot}} = 200$MN and the curvature radius of the convex base surface R_z equal to: $1 - \infty$, 2 – 10000 m, 3 – 6000 m, 4 – 4000 m.

Diagrams of the calculated values are shown in figure 5 and figure 6, and in figure 7 shows the process of developing cracks and fracture lines on it and the lower surfaces of the slab when increasing the curvature of the convex base surface.

With the curvature radius $R_{z,\,u_1} = 4000$ m, it is impossible to further increase the effect on the foundation because at the footing support along the Y-axis (the points of maximum values of the soil reactive forces) and fracture lines are formed and develop, dividing the slab into independent parts. Thus, the load-bearing capacity of the foundation slab is exhausted.

Similar simulation is performed with the value of the total vertical load $F_{tot,\ 2} = 300$ MN and the following values of the convex curvature radius R_z: 15000 m, 12000 m, and 9000 m. The load-bearing capacity of the slab is exhausted with the curvature radius $R_{z,\,u_2} = 9000$ m.

The simulation results (design values, development of cracks and fracture lines) are shown in figure 8, figure 9, figure 10.

3.2. Simulation with the curvature of the concave base surface

With the same slab characteristics and total vertical loads $F_{tot,\ 1} = 200$ MN and $F_{tot,\ 2} = 300$ MN, it is necessary to determine the stress-deformed state of the foundation slab by increasing the curvature of the concave base surface along the Y-axis (i.e. $\upsilon\,(r,\,\varphi) = \upsilon\,(x)$, figure 11, figure 12, figure 13).

The following values of the conventional curvature radii of the concave base surface R_z are

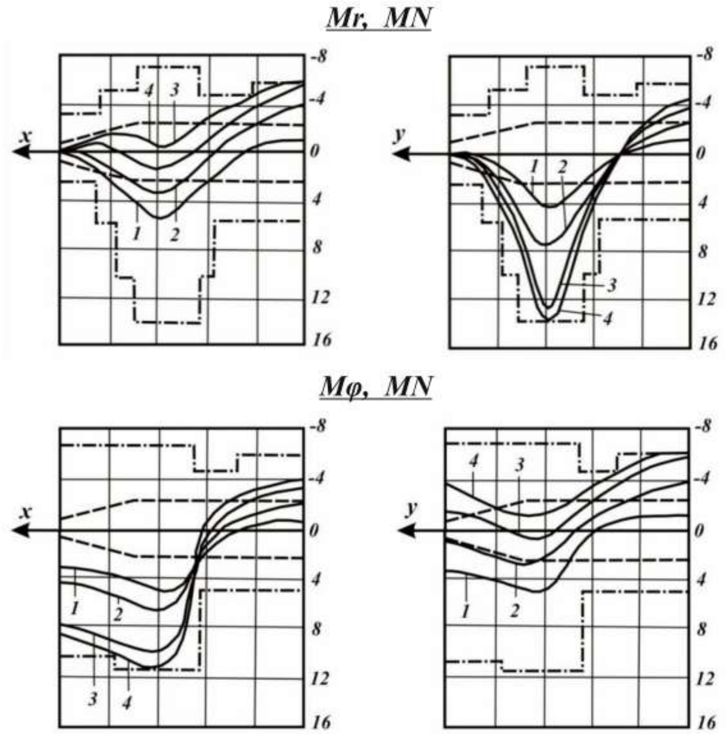

Figure 6. Radial M_r and annular M_φ moments in the foundation slab along the central axes OX and OY with increasing curvature of the convex base surface: 1 – ∞, 2 – 10000 m, 3 – 6000 m, 4 – 4000 m.

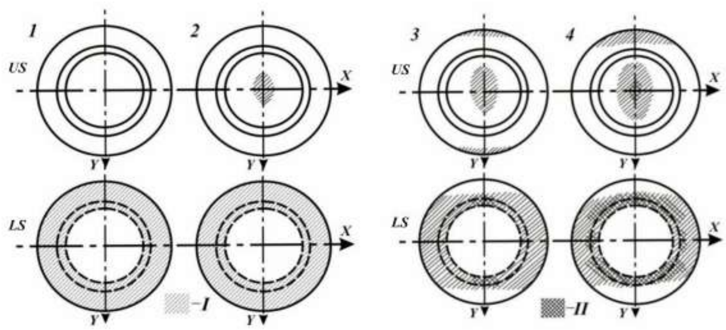

Figure 7. Development of elastic deformation zones in the foundation slab when increasing curvature of the convex base surface: *US, LS* – upper and lower slab surfaces; *I, II* – zones of formation of cracks and plastic hinges; 1 – ∞, 2 – 10000 m, 3 – 6000 m, 4 – 4000 m.

simulated: 10000 m, 6000 m, 5000 m at load $F_{tot,\ 1}$; 15000 m, 12000 m, 10000 m at load $F_{tot},\ _2$.

Reduced characteristics of the deformed base are determined according to [11]. In the first case, i.e. at $F_{tot,\ 1}$, the load-bearing capacity of the structure is exhausted at the value $R_{z,\,u_1}=$ 5000 m, and in the second case (for $F_{tot,\ 2}$), at $R_{z,\,u_2}=$ 10000 m. The simulation results are shown in figure 14, figure 15, figure 16.

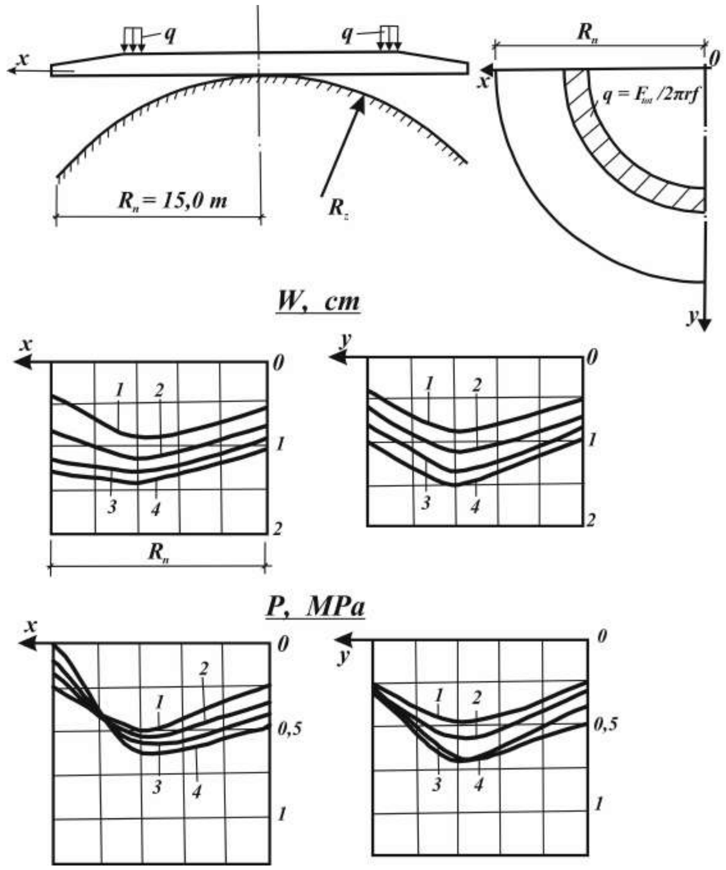

Figure 8. Settling W and contact pressures P along the central axes OX and OY with the vertical load $F_{\text{tot}} = 300\text{MN}$ and the curvature radius of the convex base surface R_z equal to: 1 – ∞, 2 – 15000 m, 3 – 12000 m, 4 – 9000 m

3.3. Simulation with the base settling at the end of the foundation

It is necessary to investigate the behaviour of the round foundation slab with different values of the settling section of the base at the end of the foundation.

The slab undergoes the following loads: the total vertical load $F_{tot} = 200$ MN, the external moment $m_1 = 150\ MNm$. The height of the centre of gravity of the structure relative to the foundation bed $Hc = 75\ m$.

The simulation is carried out with the length of the settling section (ledge) $\ell_y = R_n$ and the height h_y equal to 0.100 m, 0.200 m, and 0.25 m. The characteristics of the settling section are determined according to [30–32].

The simulation results are shown in figure 17, figure 18, figure 19.

With the settling section $\ell_y = R_n$and $h_y = 0.25$ m, the resulting roll begins to increase sharply ($\theta_2 = 0.0120$) and reaches the limit value set by the standards for the structure.

A further increase in the roll leads to a loss of stability of the foundation slab position; therefore, the load-bearing capacity of the structure is exhausted. At the same time, the fracture lines are at the initial stage of development.

3.4. Analysis of simulation results

The simulation results show that the stress-deformed state of the round foundation slab and the patterns of its load-bearing capacity (zones of formation and development of plastic hinges)

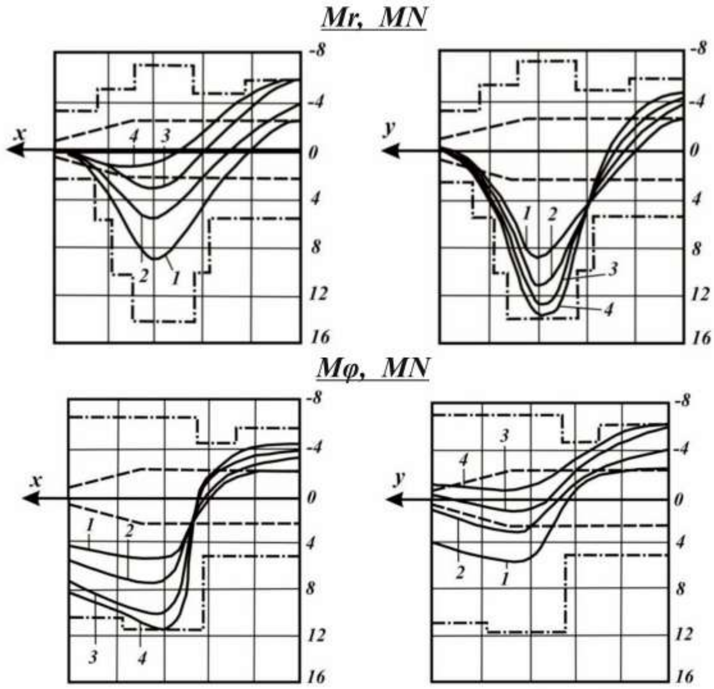

Figure 9. Radial M_r and annular M_φ moments in the foundation slab along the central axes OX and OY with increasing curvature of the convex base surface: 1 – ∞, 2 – 15000 m, 3 – 12000 m, 4 – 9000 m.

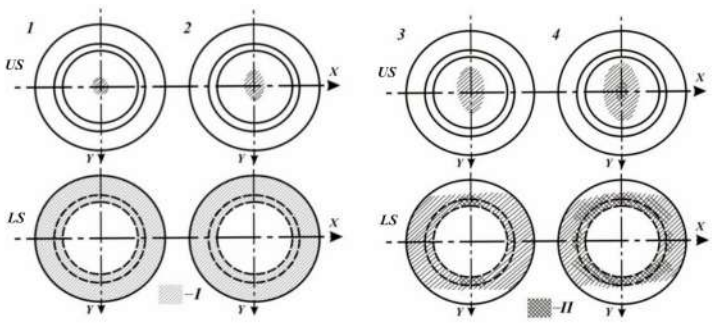

Figure 10. Development of elastic deformation zones in the foundation slab with increasing the curvature of the convex base surface: *US, LS* – upper and lower surfaces of the slab; *I, II* – zones of formation of cracks and plastic hinges; 1 – ∞, 2 – 15000 m, 3 – 12000 m, 4 – 9000 m.

under non-uniform deformation of the base surface are different from the type of change in the shape of the base surface.

The main zones of formation and development of fracture lines in the slab under various deformation conditions of the base are shown in figure 20. Under normal soil conditions, such zones are footing support points (figure 20, *a*). There may also be cracks on the upper surface of the central part of the slab.

When the convex base surface is curved along the Y-axis, the radial bending moments increase along this axis and fracture lines are formed at the footing support points. In the annular direction, the structure is unloaded at these points, and in the central part it is actively deformed and the moments reach the limit values.

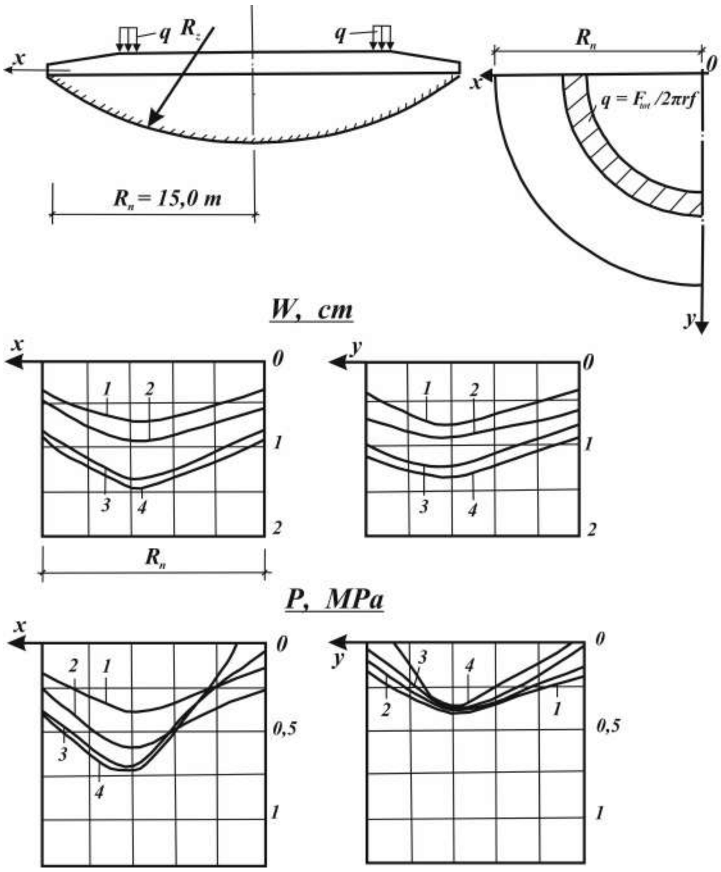

Figure 11. Settling W and contact pressures P along the central axes OX and OY with the vertical load $F_{\text{tot}} = 200$MN and the curvature radius of the concave base surface R_z equal to: $1 - \infty$, $2 - 10000$ m, $3 - 6000$ m, $4 - 5000$ m.

Along the X-axis in the radial direction, there is load release at footing support points and active deformation to the limit states at the centre. As the curvature of the base surface increases, annular moments increase at the points where the load is applied and reach the limit values.

In the central part, they do not change significantly. Note that with the curvature of the convex base surface along the Y-axis, reactive pressures of the soil are concentrated along this axis, resulting in the development of fracture lines and the collapse of the structure (figure 20, b).

Along the X-axis, fracture lines are about to develop from the cantilever part of the slab. It should be noted that with different values of the vertical load F_{tot}, the bearing capacity of the slab is exhausted at different curvature values of the convex base surface. At the same time, the higher the value of the vertical load is, the smaller the value of the curvature becomes.

With the curvature of the concave base surface along the Y-axis, the following patterns of the changed stress-deformed state of the foundation slab can be noted. The reinforced concrete slab is unloaded at the footing support points along the Y-axis in the radial direction and along the X-axis in the annular direction. It is actively deformed along these axes in the corresponding directions at its centre. The radial moments along the X-axis and the annular moments along the Y-axis are maximally increased to the limit values at the footing support points. Fracture lines at these points exhaust the load-bearing capacity of the foundation slab.

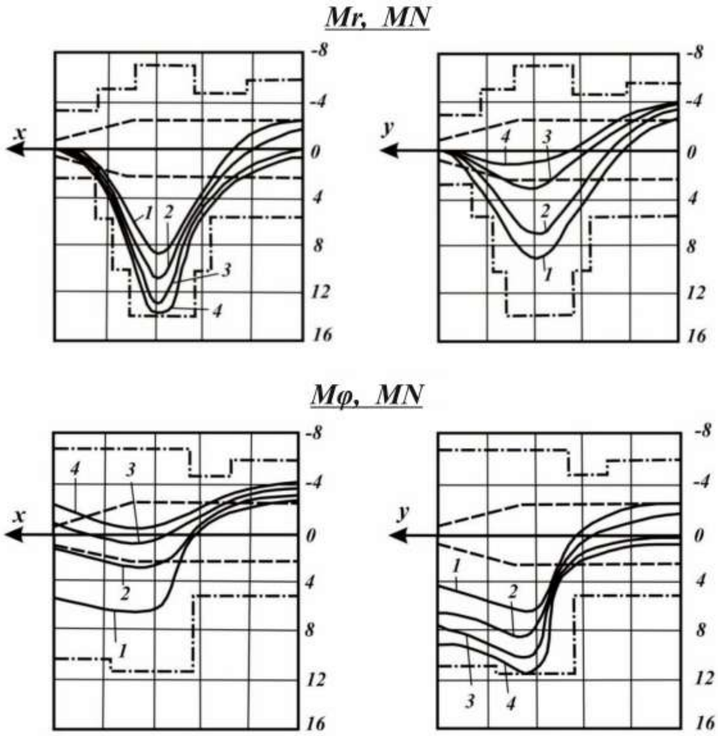

Figure 12. Radial M_r and annular M_φ moments in the foundation slab along the central axes OX and OY with the increased curvature of the concave base surface: 1 – ∞, 2 – 10000 m, 3 – 6000 m, 4 – 5000 m.

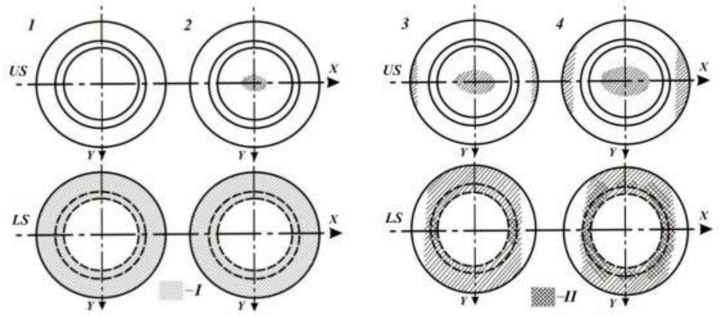

Figure 13. Development of elastic deformation zones in the foundation slab with the increased curvature of the concave base surface: *US, LS* – upper and lower slab surfaces; *I, II* – zones of formation of cracks and plastic hinges; 1 – ∞, 2 – 10000 m, 3 – 6000 m, 4 – 5000 m.

Thus, with the curvature of the concave base surface along the Y-axis, the slab begins to collapse in the perpendicular direction along which the maximum reactive forces from the base side are located (figure 20, *c*). Along the Y-axis from the cantilever part of the slab, radial fracture lines begin to develop simultaneously.

At different values of the vertical load, the load-bearing capacity of the slab is exhausted at different curvature values of the concave base surface. At the same time, the higher the load is, the smaller the curvature value becomes.

It is important to note that with the same values of the vertical load F_{tot}, the load-bearing

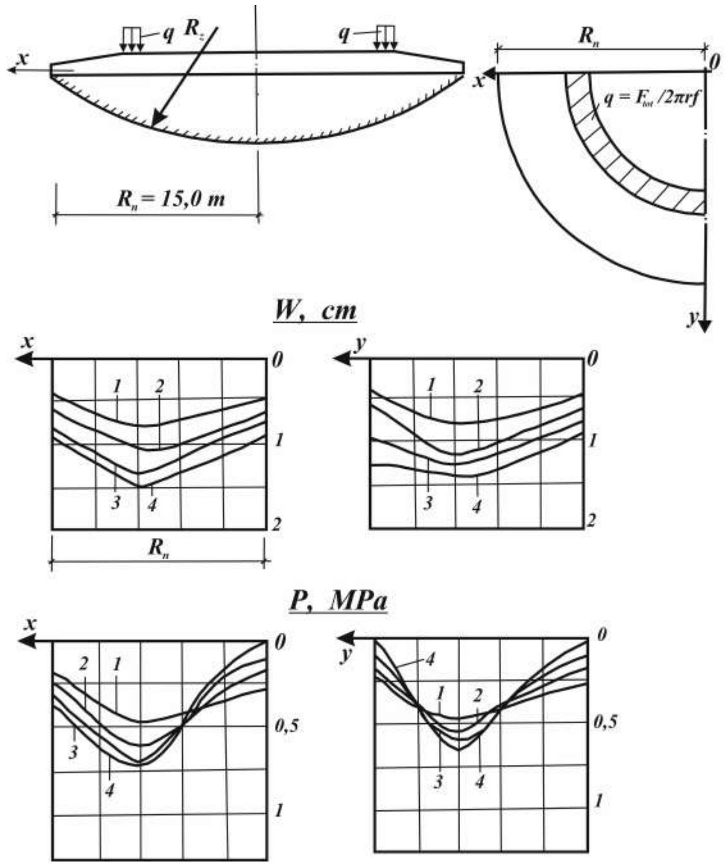

Figure 14. Settling W and contact pressures P along the central axes OX and OY at the vertical load $F_{\text{tot}} = 300\text{MN}$ and the curvature radius of the concave base surface R_z, equal to: $1 - \infty$, $2 - 15000$ m, $3 - 12000$ m, $4 - 10000$ m.

capacity of the foundation slab is exhausted at curvature radii of the convex base surface slightly less than the corresponding concave curvature radii.

If the end of the foundation has a ledge with the line parallel to the Y-axis, the contours of the calculated values are almost unchanged along this axis. The annular bending moments increase significantly in the central part of the foundation, which leads to the formation and development of cracks (further fracture lines) on the upper surface of the slab. In the perpendicular direction at the footing support points, the radial and annular moments increase towards the settling section of the base, and on the opposite side the structure is unloaded. In the central part of the slab, radial moments increase significantly, which causes the formation and development of cracks and fracture lines on the upper surface of the slab (figure 20, d). Fracture lines begin to develop at the places where the load is applied. In this example, the load-bearing capacity of the foundation slab is exhausted not due to destruction, but due to loss of stability. In the general case of an unstable position of the foundation structure, the exhaustion of its load-bearing capacity should be checked for two reasons (destruction and loss of stability).

4. Conclusions

1. New patterns of determination of internal forces for possible conditions of the first and second category elements of the reinforced concrete slab under complex load are established. The characteristic feature of the second category elements in the passive deformation state

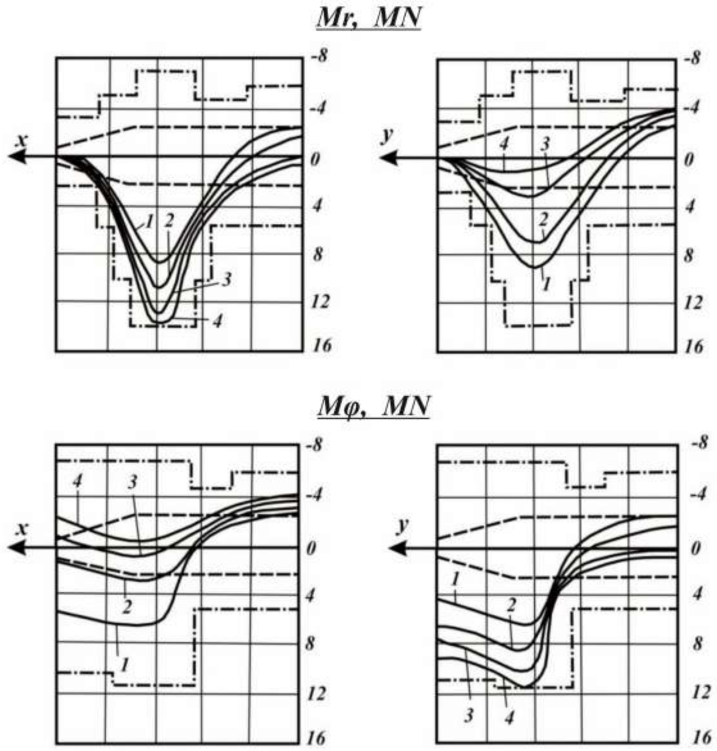

Figure 15. Radial M_r and annular M_φ moments in the foundation slab along the central axes OX and OY with the increased curvature of the concave base surface: 1 – ∞, 2 – 15000 m, 3 – 12000 m, 4 – 10000 m.

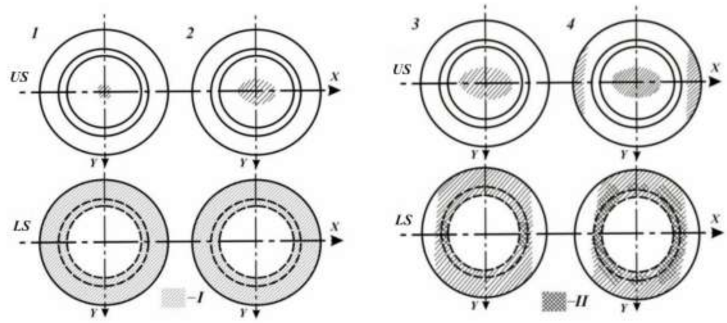

Figure 16. Development of elastic deformation zones in the foundation slab with the increased curvature of the concave base surface: *US, LS* – upper and lower slab surfaces; *I, II* – zones of formation of cracks and plastic hinges; 1 – ∞, 2 – 15000 m, 3 – 12000 m, 4 – 10000 m.

is the determination of the moment corresponding to the curvature of the load-release curve.

2. The introduction into the calculation of the function characterizing the degree of reduction of the weakened base characteristics to determine the variable stiffness coefficient in load release allows taking into account the conditions of contact interaction of the slab and the non-uniformly deformed base. Dependences of the weakened base for collapsible soils, underworked areas, and karsted areas are obtained.
3. The developed programme allows taking into account the load history of elements using

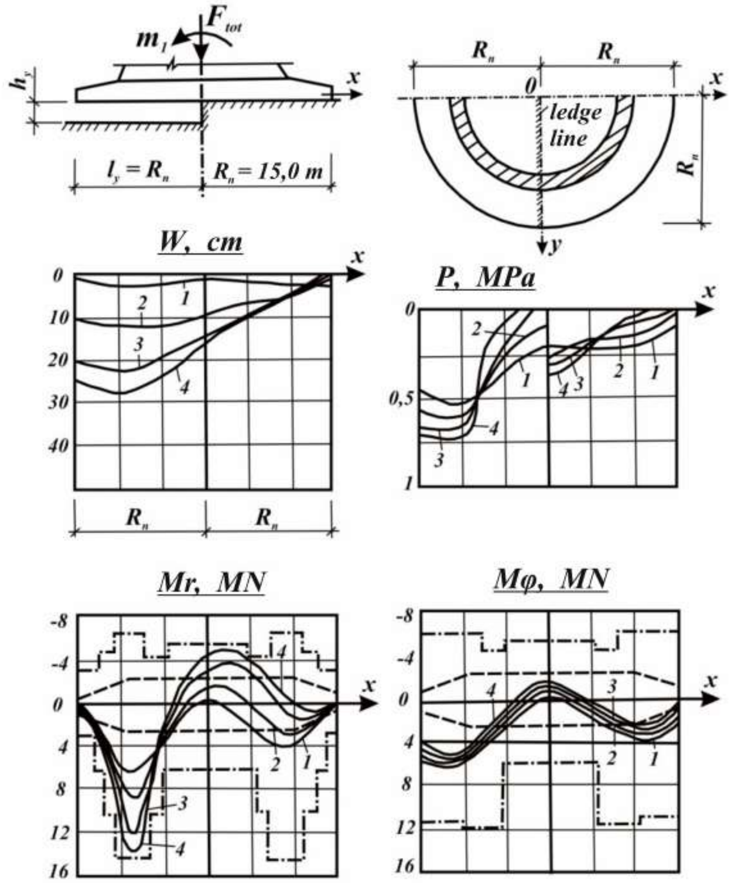

Figure 17. Design values along the OX-axis with the vertical load $F_{\text{tot}} = 200$MN, the external moment $m_1 = 150$MNm, and the settling section of length and height at the end of the foundation equal to: 1 – 0, 2 – 10 cm, 3 – 20 cm, 4 – 25 cm.

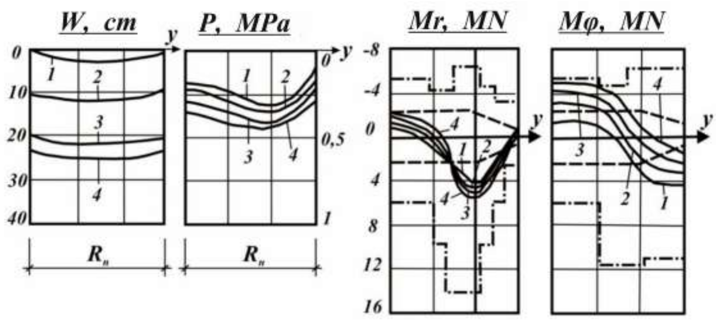

Figure 18. Design values along the OY-axis with the increased settling section: 1 – 0, 2 – 10 cm, 3 – 20 cm, 4 – 25 cm.

non-linear diagrams in the entire range of force and deformation effects.

4. On the basis of the analysis of the obtained simulation results of slab operation on the non-uniformly deformed base under complex loads, the following conclusions can be drawn:
   - at the curvature of the convex base surface along one axis, the maximum plastic deformation zones of the foundation structure are located on both sides of this axis,

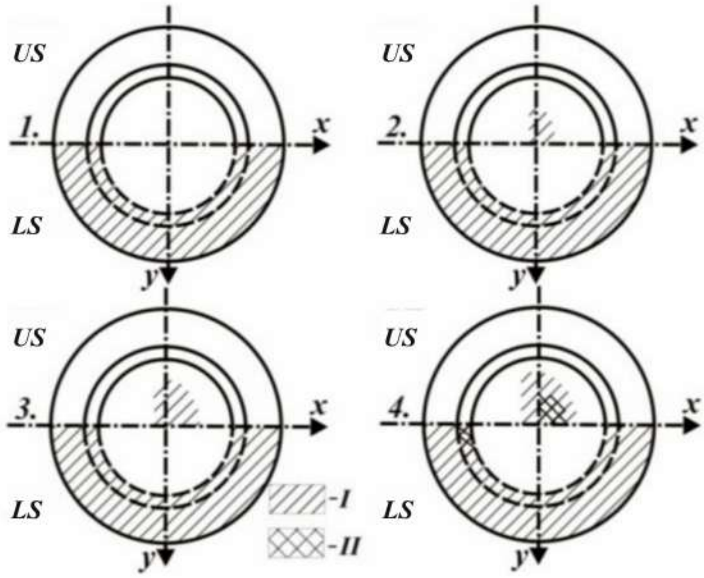

Figure 19. Development of cracks and fracture lines with the increased settling section: *US, LS* – upper and lower surfaces of the slab; *I, II* – areas of formation of cracks and plastic hinges; 1 – 0, 2 – 10 cm, 3 – 20 cm, 4 – 25 cm.

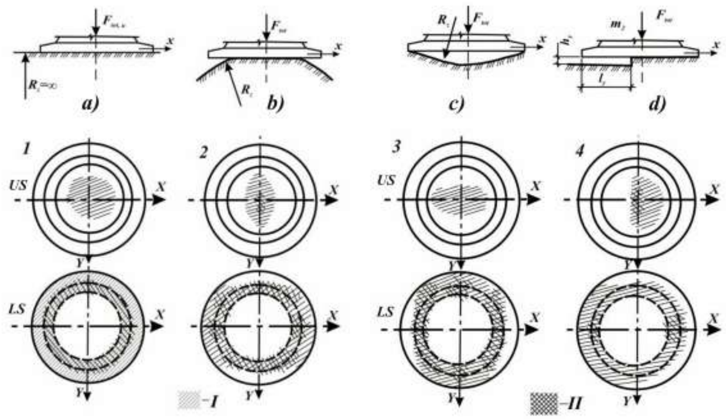

Figure 20. Zones of developed elastic plastic deformations in the round foundation plate under different deformation conditions of the base: *a)* normal soil conditions; *b)* convex surface of the base; *c)* concave surface of the base; *d)* ledged surface of the base; *US, LS* – upper and lower surfaces of the plate; *I, II* – zones of formation of cracks and plastic hinges.

and the slab is destroyed by fracture lines formed and developed in these zones;

- at the curvature of the base surface, the zones of plastic deformations of the structures are located mainly in the places of reactive soil pressures concentration;
- the curvature of the convex base surface, and to a lesser extent the bearing capacity adversely affect the operation of the foundation slab as compared with the curvature of the concave at the same values of the vertical load F_{tot};
- depending on the size of the settling section at the end of the foundation, the load-bearing capacity of the structure may be exhausted either due to destruction caused by the formation of plastic hinges or due to loss of position stability caused by large

inadmissible rolls;

- the value of the limit load on the slab decreases with the increase of deformation effects of the base on it;
- under non-uniform deformations of the base, the main areas of destruction of round foundation slabs are the footing support points, but in some cases (curvature of the base surface, settling of the base at the end of the foundation) such zone may occur in the central part of the slab.

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Effect of sodium metasilicate on the early-age hydration and setting behavior of alkali-activated common cements containing slag

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Abstract. The ways to keep under regulation the early-age hydration and setting behavior of the common cements containing slag per EN 197-1:2011 and activated with sodium metasilicate were discovered and the results are discussed. The alkaline activation of these cements using sodium metasilicate is one of the ways to escape the strength loss in the cement systems with blast-furnace slag content of 5…95 %. However, these cements have too short setting times. This requires finding ways to regulate the structure formation. The aggregate states of sodium metasilicate, thesWe were: a liquid state (solution) and a solid state (powder) as well as the admixture-surfactant have been chosen as factors of influence to regulate setting times. The results of the study showed that the use of sodium metasilicate in the liquid state, on contrary to the solid state, provided additional intensification of the structure formation. The acceleration of the structure formation processes was accompanied by the formation of high early (1 day) compressive strength of 43…54 MPa, associated with an extremely quick setting time of 1…8 min. The sodium lignosulphonate admixture could be of help: its addition in a quantity of 4 % can retard the structure formation processes to the required ranges, not depending upon the aggregate state of sodium metasilicate. The resulting alkali-activated common cements containing slag are characteristic of the early (1 day) compressive strength of 33…48 MPa and initial setting time of 38…50 min.

1. Introduction

In recent decades, a lot of concrete structures (highways, pavements of airports, bridge decks, tunnels, tank depots, fortifications, etc.) have undergone degradation under external loads and environmental influences. The damages reduce the durability of such structures as well as cause less functionality during operation [1,2]. The mentioned facts actualize the development of cost-effective and efficient rapid-hardening high strength concretes and mortars of new generation [3], such as concretes for repairing building construction [4,5], shotcretes [6,7], underwater concretes [8–10], reactive powder concretes [11,12], mortars for anchoring [13,14], etc.

Polymers (epoxy resin, acrylic, resin, polyurethane, and acrylamide) are considered effective in some mentioned materials (repair materials, for example) due to high values of compressive strength after 28 d – up to 100 MPa and flexural strength after 28 days – up to 20 MPa [15]. However, limiting factors for the application of such materials are their high cost, reduced durability under the influence of ultraviolet radiation, as well as flammability and smoke release [16–18].

Cements are also widely used in rapid-hardening materials [19–21]. Portland cement [22, 23], magnesium phosphate cements [24, 25], calcium aluminate cements [26, 27], and calcium sulphoaluminate cements [28, 29] are the most commonly used.

The high early strength of rapid Portland cement relies on high percentages of C_3S and C_3A to give rapid hardening and setting [30]. The high early strength of concretes and mortars (≥ 40 MPa at an age of 1 day) can be achieved with a higher specific surface and high OPC content, low water-to-cement ratio (further, W/C), and the use of admixtures-accelerators [31–34].

The magnesium phosphate-based materials and the calcium aluminate-based materials are characterized by high early compressive strength (≥ 20 MPa in 2…3 h) [35, 36]. These cements and concretes based on them are expensive and some of them are not commercially produced in the Ukraine, for example, the calcium aluminate cement, which, above all, has unstable strength at a later age, especially at temperatures over 25 °C.

The perspective direction is the use of alkali-activated cements made using the common cements containing slag per EN 197-1:2011. The alkali-activated cements have high strength and meet the goals of global sustainable development [37–39] due to a comprehensive approach to the saving of natural materials resources and energy and can be considered "environmentally responsible materials".

Depending on the precursor (aluminosilicate component), certain phase ratios are formed in $CaO - Al_2O_3 - SiO_2 - H_2O, R_2O - CaO - Al_2O_3 - SiO_2 - H_2O, and R_2O - Al_2O_3 - SiO_2 - H_2O$ systems [40]. The phase ratio determines the structure of a resulting cement matrix and its properties [37, 41].

Sodium silicates, the anions of which are similar to hydrated initial products of destruction of the alumina-silica-oxygen framework, and serve as their additional reserve [37], are found to be the most effective alkaline activators for rapid hardening alkali-activated cements. The best solution is the use of sodium metasilicate pentahydrate (further, sodium metasilicate) due to its constant composition, market availability in a solid state (powder), and easiness-in-use in the process of cement and concrete manufacture.

The main obstacle in using the alkali-activated cements made with sodium metasilicate is an extremely quick setting [42]. The aggregate state of sodium metasilicate is a factor to be provided high strength of alkali-activated cements but could ensure extremely short setting times [43]. This resulted in a necessity to find ways to regulate the structure formation processes in these cements.

The use of the potassium fluoride admixture as a setting retarder is reported in [44]. However, this admixture can increase the cost of the alkali-activated cements and is classified as toxic compound.

One such setting retarder for the alkali-activated cements is $Na_3PO_4 12H_2O$, however, it could work effectively only with soluble sodium silicate with $M_s \geq 2$ [45].

The use in the alkali-activated cements of traditionally used admixtures-setting retarders was found to be ineffective because of the instability of a molecular structure in a liquid phase of the ones [46]. Sodium lignosuphonates were also found to be highly effective setting retarders for the alkali-activated cements [47].

The use of sodium metasilicate, despite its high potential, is a question from the point of view of setting times, and a choice of ways to keep the structure formation in the alkali-activated cements under regulation and provide acceptable setting times, in this case is an actual task.

The task of the study was to discover an approach to regulate the early-age hydration and setting behavior of the alkali-activated common cements containing slag through alkaline activation with the help of sodium metasilicate.

2. Raw materials and testing techniques

Used as components of the common cements containing slag were :

- Portland cement clinker (further, clinker) (% by mass: CaO – 67.60, SiO_2 – 20.84, Al_2O_3 – 5.12, Fe_2O_3 – 3.99, MgO – 0.78, SO_3 – 0.87, $Na_2O + K_2O$ – 0.80) with specific surface – 390 m^2/kg (by Blaine);
- ground-granulated blast furnace slag (further, GGBFS) (% by mass: CaO – 48.20, SiO_2 – 37.90, Al_2O_3 – 6.80, Fe_2O_3 – 0.30, MgO – 5.21, MnO – 0.11, TiO_2– 0.35, $Na_2O + K_2O$ – 0.35) with a basicity modulus - 1.18, glassy phase - 84.0 %, and specific surface – 400 m^2/kg (by Blaine).

The preparation of cement specimens was done by mixing the above-listed components. Used in the study were three cement systems (No 1, 2, and 3), the compositions of which are given in table 1.

To evaluate the basicity of the cement systems under study, a modulus of basicity, similar to that used in the evaluation of the basicity of GGBFS, namely: $M_b = (CaO + MgO)/(SiO_2 + Al_2O_3)$ – a ratio of masses of oxides, was applied [42].

Table 1. Compositions of three cement systems under study.

Cement system	Modulus of basicity, M_b	Content of clinker, % by mass	Content of GGBFS, % by mass
No 1	2.5	95	5
No 2	1.7	50	50
No 3	1.2	5	95

Used as an alkaline component was sodium metasilicate ($Na_2O \cdot SiO_2 \cdot 5H_2O$) in a solid aggregate state (a non-hygroscopic powder) and in a liquid aggregate state (a solution with a density of 1.24 g/ml). Sodium metasilicate was added in two aggregate states, both in equal quantities – 12 % (calculated on dry matter) or 3.5 % (calculated on Na_2O).

Used as a setting retarder was sodium lignosulphonate (further, LS) in the form of a concentrated solution with density of 1.25 g/ml and concentration of 45 %. The quantity of the admixture was 4 % (calculated on dry matter) (over 100 %).

The cement pastes were prepared in a standard Hobart mixer.

The setting times were measured per EN 196-3:2005 Standard.

The compressive strength of the cements was determined per EN 196-1:2016 Standard with the following amendment: W/C or solution-to-cement ratio (further, S/C) in case of dry state and liquid state of alkaline component accordingly was chosen in such a way that its consistency evaluated by flow would be 106…115 mm per National Standard of Ukraine DSTU B V.2.7-187:2009 (against a standard W/C = 0.5).

Calorimetry was used to study the influence of cement basicity, the aggregate state of the alkaline component, and sodium lignosulphonate admixture.

The heat of hydration of cement pastes was measured using a modified semi-adiabatic calorimetry, the details of which are given in [48]. The initial temperature of the constituents at the moment of mixing was $t = 20 \pm 1$ °C. The frequency of measurements varied from 15 sec and up to 5 min. The W/C in the cement pastes was 0.5. The study of structure formation processes in the cement systems was evaluated under the known criteria [49–51].

3. Results and discussions

3.1. The influence of basicity of the cement systems

The use of cement systems with various basicities varying from $M_b = 2.5$ to $M_b = 1.2$ with the increase of the slag constituent from 5 to 95 % by mass requires developing a different approach

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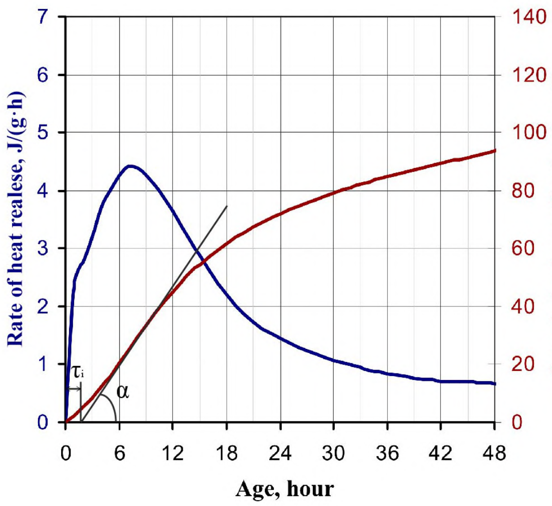
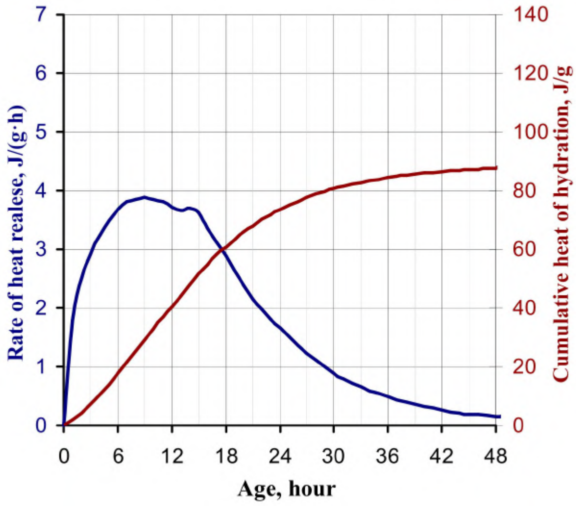
to regulate the structure formation processes.

3.1.1. Heat evolution. The early structure formation processes in the cements made with sodium metasilicate powder, depending upon the cement basicity, were studied.

The influence of the basicity on the structure formation processes is shown in figure 1. In all three alkali-activated (AA) cement systems under study made with sodium metasilicate powder, the wetting of active centers of a solid phase took place very quickly, within a few minutes, and a coagulation structure was formed. With increasing the GGBFS content from 5 % to 95 %, the duration of the induction period increased from 50 min (figure 1a) to 6 h (figure 1c). The duration of the induction period (τ_i) was determined using a tangent to a curve of cumulative heat of hydration.



(*a*)



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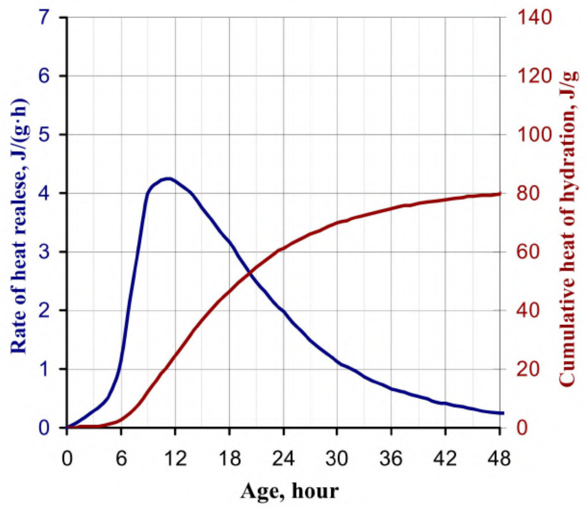

(*c*)

Figure 1. Rate of heat release and cumulative heat of hydration of alkali-activated cement systems No 1 (*a*), No 2 (*b*), and No 3 (*c*) with sodium metasilicate powder vs.age.

The formation of the condensation-crystallization structure of the AA cement systems is accompanied by the increase in the rate of heat release. The rate of hydration was evaluated using a tangent angle (α) to the curve of cumulative heat of hydration [50]. With increasing the GGBFS contents from 5 % up to 95 %, the rate of hydration remained without changes – at a level of 50…52 J/(g·h) (figure 1). At the same time, the degree of hydration (cumulative heat of hydration at an age of 24 h) of the AA cement systems for the above-specified GGBFS contents decreased from 72 J/g (figure 1a) to 60 J/g (figure 1c). The effects in the curves of the rate of heat release of the AA cement systems are caused, chiefly, by condensation of seeds of low-calcium silicate hydrates [37]. The presence of two effects in the case of AA cement system No 2 can be attributed to a joint participation of GGBFS and clinker in the hydration processes.

Above all, with decreasing the AA cement system basicity from M_b= 2.5 to M_b= 1.2, the structure formation processes retarded, and this was supported the shift of the effect on the rate of heat release from 7 h (figure 1a) to 11 h (figure 1c).

3.1.2. Setting times. The initial and final setting times of the AA cement system with 5 % of GGBFS and sodium metasilicate powder were 8 min and 11 min, and those of the AA cement system with 50 % of GGBFS – 19 min and 25 min. These initial setting times cannot be accepted for the alkali-activated cements per National Standard of Ukraine (DSTU B V.2.7-181:2009), under which a value of $\geq$ 30 min is specified. With further increasing of the GGBFS content up to 95 %, the setting times reached the standard-specified values: initial setting time – 100 min, final setting time – 130 min. The obtained results correlate well with the data of the thermokinetic analysis, according to which the higher the content of the slag constituent in the AA cement system, the longer the duration of the induction period.

3.1.3. Compressive strength. With increasing the GGBFS content from 5 % to 95 %, the compressive strength of the AA cement system made with sodium metasilicate powder at an age of 2 days decreased from 39 MPa to 32 MPa while decreasing W/C from 0.35 down to 0.34 (figure 2). The discovered dependence coincided to the results obtained from the thermokinetic analysis, namely: the retarded rate of the structure formation at early ages of hardening (up to 2 days).

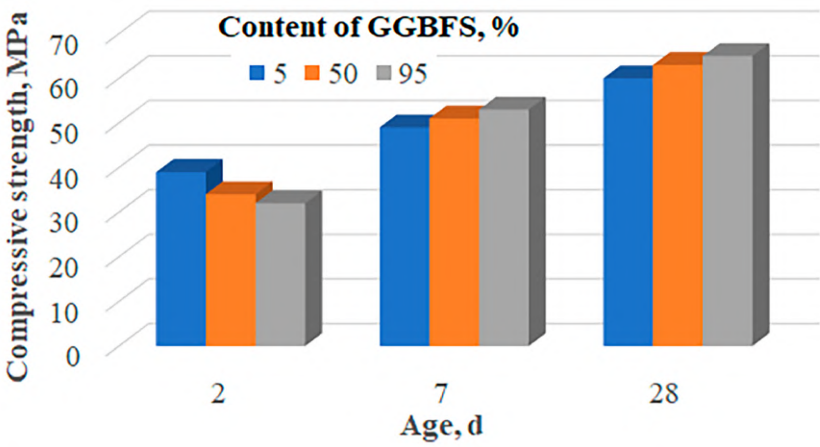

Figure 2. Comparative compressive strength of the alkali-activated cement systems with sodium metasilicate powder vs. content of GGBFS and age.

At later ages, the rate of strength gain, depending upon the basicity, varied. With increasing the content of the slag constituent from 5 % to 95 %, the compressive strength increased: at an age of 7 days – from 49 MPa to 53 MPa, at an age of 28 days – from 60 MPa to 65 MPa. This result can be attributed to the greater activating effect of sodium metasilicate powder on the clinker constituent at the early stages of hardening compared to that of GGBFS. At that, with time, the activating effect of the alkaline component on the slag constituent prevailed over that of the clinker constituent.

The obtained results testify to the necessity of retarding the early structure formation in the AA cement systems containing slag in quantities of 5. . . 50 % and made with sodium metasilicate powder to obtain the acceptable setting times.

3.2. The influence of the aggregate state of sodium metasilicate

Two aggregate states of sodium metasilicate added to the AA cement systems (powder and solution) require further studying of their effect on the structure formation.

3.2.1. Heat evolution. The effect of the aggregate state of sodium metasilicate was studied using AA cement system No 3 as the best in terms of setting times.

With sodium metasilicate solution compared to that in powder form, the duration of the induction period decreased to 1 h (figure 3) (against 6 h (figure 1c) of the AA cement system with sodium metasilicate powder). This can be attributed to the fact that in the case of powder, a certain time is required for the dissolution of sodium metasilicate in mixing water and its involvement in structure formation processes. In the case of sodium metasilicate solution, these processes occur and start to develop immediately and with a higher intensity. The rate of hydration increased to 59 J/(g·h) (against 52 J/(g·h)), and the degree of hydration to 78 J/g (against 60 J/g).

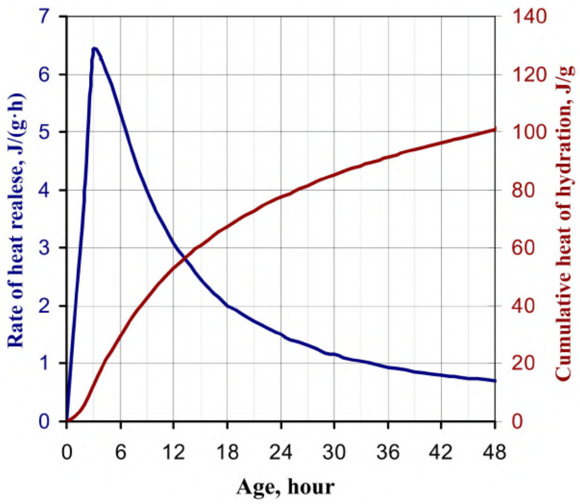

Figure 3. Rate of heat release and cumulative heat of hydration of alkali-activated cement system No 3 made with sodium solution vs.age.

The use of sodium metasilicate solution instead of powder allowed to shift the effect in the curve of the rate of heat release from 11 h to 3 h, thus supporting a conclusion on the intensification of the structure formation processes.

3.2.2. Setting times. The comparison of the setting times of the AA cement systems made with sodium metasilicate solution and with powder showed the quicker initial setting times in the case of solution: AA cement system No 1 (1 min against 8 min), AA cement system No 2

(4 min against 19 min), and AA cement system No 3 (8 min against 100 min) associated with the shorter final setting times – 2 min against 11 min (AA cement system No 1), 6 min against 25 min (AA cement system No 2), and 12 min against 130 min (AA cement system No 3). The obtained results correlated well with the thermokinetic analysis data testifying on the shorter duration of the induction period in the case of sodium metasilicate solution compared to sodium metasilicate powder (figure 3). These initial setting times were too short and could not be accepted for the AA cement systems per DSTU B V.2.7-181.

3.2.3. Compressive strength. In the case of the use of sodium metasilicate solution, the rate of strength gain is similar to that of sodium metasilicate powder, not depending upon the cement basicity. The early (1 day) compressive strength of the AA cement systems made with sodium metasilicate solution within the range of the contents of GGBFS of 5...95 % decreased – 43 MPa with S/C of 0.35 (against 54 MPa with W/C of 0.34) (figure 4). The compressive strength at ages of 7 and 28 days increased: 92 MPa (against 86 MPa) and 115 MPa (against 103 MPa).

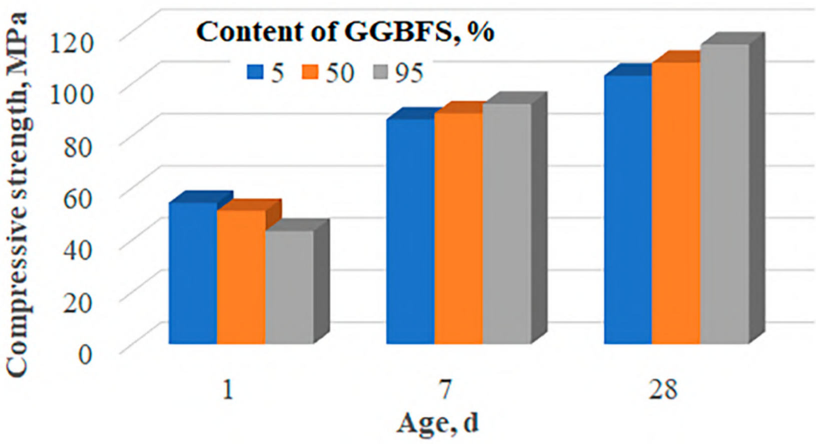

Figure 4. Comparative compressive strength of the alkali-activated cement systems made with sodium metasilicate solution vs. content of GGBFS and age.

The use of sodium metasilicate solution compared to sodium metasilicate powder resulted in a shorter duration of the induction period and, respectively, too quick setting, despite high early (1 day) compressive strength – 43...54 MPa (S/C= 0.33...0.34).

The obtained results testify to a necessity to decelerate the rate of structure formation in the AA cement systems for the whole range of contents of the slag constituent and made with sodium metasilicate solution to provide the standard-specified setting times.

3.3. The influence of the admixture on the structure formation

The influence of the LS admixture was studied using AA cement system No 3 made with sodium metasilicate solution with the account of its quick setting. The quantity of the LS admixture was 4 % of the mass of the cement system.

3.3.1. Heat evolution. The addition of the LS admixture resulted in a longer induction period (from 1 h (figure 3) to 5 h (figure 5)), the rate of hydration decreasing from 59 J/(g·h) to 48 J/(g·h), the degree of hydration – from 78 J/g to 62 J/g. A shift of the effect in the curve of the rate of heat release from 3 h (figure 3) to 13 h (figure 5) was a result of the influence of the admixture.

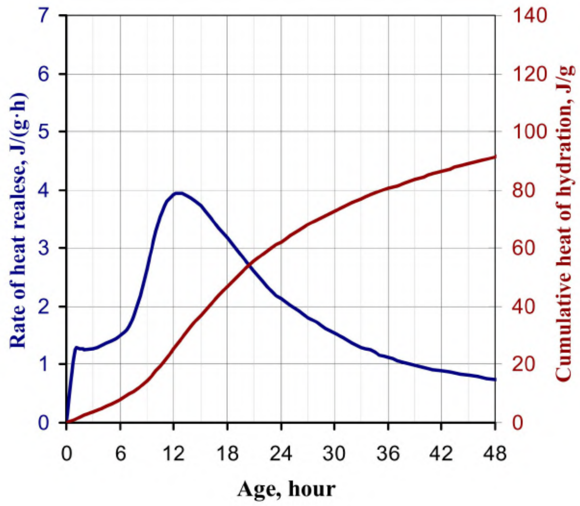

Figure 5. Rate of heat release and cumulative heat of hydration of alkali-activated cement system No 3 made with sodium metasilicate solution and the LS admixture vs. age.

The changes of the thermokinetic characteristics in the case of the LS admixture were reflected in the retarded structure formation processes, thus allowing us to predict the extended setting times.

3.3.2. Setting times. With the use of the LS admixture, the initial setting times of AA cement systems No 1, No 2, and No 3 made with sodium metasilicate solution increase from 1 min to 50 min, 4 min to 38 min, and 8 min to 60 min, respectively. Correspondingly, the final setting times increase from 2 min to 64 min, 6 min to 45 min, and 12 min to 76 min. These setting times comply with the requirements of the National Standard of the Ukraine DSTU B V.2.7-181.

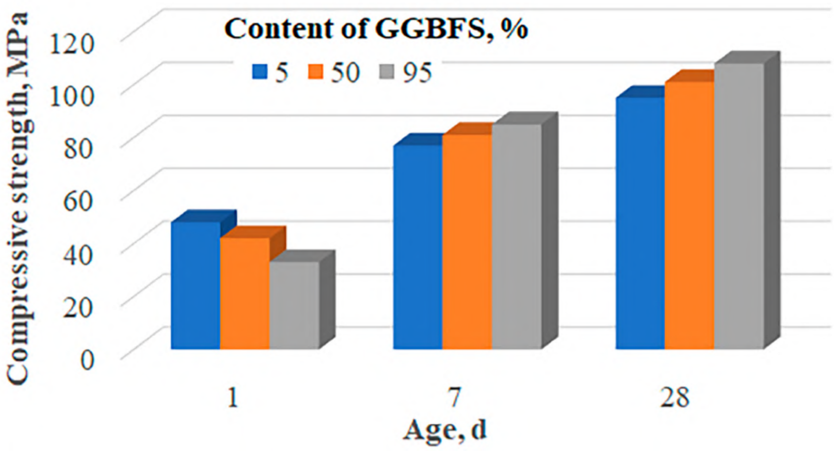

Figure 6. Comparative compressive strength of the alkali-activated cement systems made with sodium metasilicate solution and the LS admixture vs. content of GGBFS and age.

3.3.3. Compressive strength. The addition of the LS admixture to AA cement systems No 1, No 2, and No 3 made with sodium metasilicate solution resulted in some decline of the compressive strength (figure 6) compared to those of the admixture-free cement composition (figure 4): 33...48 MPa (against 43...54 MPa), 77...85 MPa (against 86...92 MPa), and 95...108 MPa (against 103...115 MPa) with S/C of 0.3...0.32 (against S/C of 0.33...0.34) at ages of 1, 7, and 28 days, respectively.

Thus, the use of the LS admixture allowed for quick hardening of the alkali-activated common cements containing slag with the acceptable setting times.

4. Conclusion

1. The basicity and the aggregate state in which sodium metasilicate pentahydrate was added were found to be the main factors determining the early-age hydration and setting behavior of the alkali-activated common cements containing slag.
2. With increasing the cement basicity from M_b= 1.2 to M_b= 2.5 through the increase of the GGBFS content from 5 % to 95 % by mass, the duration of the induction period increased by 7.2 times and was associated with the deceleration of the initial setting times from 8 min to 100 min. At the same time, the retarded processes of early structure formation in the alkali-activated common cements through the higher content of the slag constituent within the above range were accompanied by the lower degree of hydration (by 16.7 %) and the lower 2-day-compressive strength (by 17.9 %).
3. The use of sodium metasilicate in a liquid aggregate state (solution) instead of a solid aggregate state (powder) was accompanied by the acceleration of the structure formation processes in the alkali-activated common cements. This conclusion was supported by the shorter duration of the induction period, and the higher rate and degree of hydration. The more intensive structure formation processes in the alkali-activated common cements made with sodium metasilicate solution resulted in a high (1 day) compressive strength of 43...54 MPa associated with too quick initial setting times (1...8 min).
4. The extension of the setting times of the alkali-activated common cements could be achieved by using the admixtures – surfactants. The admixture-modified alkali-activated common cements had the decelerated structure formation and were accompanied by the longer duration of the induction period, the lower rate and degree of hydration. All this resulted in the production of quick hardening alkali-activated common cements with the compressive strength of 33...48 MPa at an age of 1 day and initial setting times of 38...50 min.

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Thermo-responsive hydrogels based on gelatin-alginate composition with humic acids intended for controlled drug delivery

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Thermo-responsive hydrogels based on gelatin-alginate composition with humic acids intended for controlled drug delivery

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Abstract. The purpose of this work is to create a bioactive "smart" thermo-responsive hydrogel, which, when exposed to the body with a physiological temperature of 37°C, reversibly turns into a sol, which can be used to introduce drugs into hard-to-reach places, for local and long-term delivery of drugs, as well as for reducing doses of delivered drugs. Herein, we developed and studied hydrogel systems containing gelatin, sodium alginate and humic acids. All natural molecular polymers used are low cost and have non-toxic, biocompatible, biodegradable and non-immunogenic properties. In addition, using our own technology, humic acids with antioxidant, antibacterial and anti-inflammatory activity were obtained from lignite, which provided a concrete chance for the technological use of humic acids in accordance with the "waste-to-wealth" approach. Rheological studies confirmed that the hydrogel containing 14 %wt.gelatin and 6.4 %wt. sodium alginate is thermo-reponsive and has a gel-sol transition, manifested in a sharp decrease in its kinematic viscosity at a physiological temperature of 37°C. The FTIR spectra of the gelatin-sodium alginate-H_2O and gelatin-sodium alginate-humic acids-H_2O systems turned out to be similar. The small red and blue shifts in stretching and bending vibration positions occurred due to gelatin-sodium alginate, gelatin-humic acids and sodium alginate-humic acids interactions, and are similar to those observed in the literature, in particular due to a conformational change in the secondary structure of gelatin. The results of a study of the gel-sol transition time at a physiological temperature of 37°C for samples of the developed thermo-responsive bioactive gelatin-alginate hydrogel containing 6.4 %wt. sodium alginate and 14%wt. gelatin, as well as samples of this hydrogel modified with different contents of humic acids, visually showed a sharp increase in the transition time from 6 min to 11 min as a result of adding 2.5 %wt.humic acids. Thus, these studies showed that relatively small concentrations of humic acids can provide a prolonged drug delivery effect through the use of gelatin-sodium alginate hydrogel modified with humic acids on the surface of the human body.

1. Introduction

1.1. Smart hydrogels

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].

Currently, a large amount of research is driven by the potential applications of hydrogels based on molecular biopolymers and their composites with various molecular substances of biological origin in various fields such as food, cosmetics, nanoelectronic devices, tissue engineering and drug delivery [2]. The reason is the ability of such "smart" hydrogels to respond to external stimuli by changing their phase state, that is, a reversible transition from sol to gel and back due to the formation/destruction of non-covalent bonds (hydrogen bonds, π-π stacking, Van der Waals etc.) [3]. The literature provides data on hydrogels of molecular biopolymers and their composites that undergo a reversible liquid–viscoelastic hydrogel phase transition depending on temperature, pH, or ionic strength of the medium. Of particular interest are thermo-responsive hydrogels that exhibit a sol-to-gel transformation that is triggered by proper physiological stimuli, such as exposure to body temperature at 37 °C [2]. For example, in [3], a graft copolymer of SA bearing eight poly(N-isopropylacrylamide) side chains enriched with the hydrophobic comonomer N-tertiary-butylacrylamide created in the presence of Ca^2+ a biocompatible self-assembling thermo-responsive hydrogel that behaved as a soft gel at room temperature and a strong gel at a physiological temperature of 37 °C, suitable for potential bio-applications. More typical is the reversible transformation of thermo-responsive gels into sols with increasing temperature, called melting [4]. Such "smart" hydrogels belong to the class of stimulating sensitive hydrogels and have unique advantages, including the possibility of introducing a drug into a hard-to-reach location [5], local and long delivery, and reduction of the dose of the delivered medicine, as well as high adhesion to mucous surfaces. The explanation is that, according to [6], gels are materials consisting of a network of macromolecules in a continuous phase, and when temperature is applied to the gel network, it can be reversibly destroyed at the melting temperature Tm or created at the gelation temperature Tg. Such "smart" gels are usually called thermoreversible [5].

1.2. Thermo-responsive biopolymer hydrogels and their complexes

The use of biomaterials, including biopolymers, to create "smart" hydrogels is a promising area of modern science and technology. The most widely used biopolymers for this purpose are proteins (silk fibroin and gelatin (GN)) and polysaccharides (cellulose, chitosan and SA), the important features of which are low cost, renewability, biocompatibility and biodegradability [7]. GN as a natural peptide macromolecule obtained by partial collagen hydrolysis, during which the regular triple helix structure is broken down to form random coils [8]. It is a natural polyampholyte that has both positively and negatively charged groups, as well as hydroxyl groups and hydrophobic groups [7]. The positive charge of the GN is provided by the residues of arginine (Arg), lysine (Lys), hydroxylysine (Hyl), and histidine (His). The hydroxyl groups arise from the residues of hydroxyproline (Hyp), serine (Ser), threonine (Thr), and tyrosine (Tyr). The negative charge of GN macromolecule is explained by glutamic acid (Glu) and aspartic acid (Asp) residues [7]. GN is one of the most commonly used polymers whose hydrogels are thermoreversible [5]. The availability, low cost, biocompatibility, biodegradability and low antigenicity of GN make it suitable for wide range of applications in nanoelectronics, pharmaceuticals and biomedical fields. Thermoreversible physical gel GN, obtained by cooling aqueous solutions of GN to temperatures below 30 °C, undergoes a sol-gel transition [4]. The gelation temperatures in the pure GN system GN-H_2O containing 2.5 %wt. GN were in the range of 15-18°C. For 5 %wt. GN solutions, the corresponding Tg range was 20-22°C [5]. According to [4], at high concentrations (over 13 %wt.GN) and temperatures below 35°C, the thermodynamic conformation of GN chains is essentially intermolecular; at temperatures below 40 °C, GN chains undergo a progressive conformational change, known as the coil-to-helix transition, producing triple helix networks. According to data [4], at a rate of temperature change of 1 °C/min, the melting temperature Tm in the pure GN gel (GN-H_2O system) is 31°C, and at the ramp rate of 10°C/min, Tm increases to approximately 32.5°C. The Tm of a GN hydrogel with 2.5 %wt.GN is 32.4°C, and at 5 %wt. GN in the GN-H_2O system, the Tm increases to 34°C. Thus, the melting point of pure GN hydrogel is in all cases below the physiological temperature of 37°C. In accordance with [5], the properties of GN can be improved by adding compounds that could interact with GN by creating additive chemical or physical bonds to increase, on the one hand, the rheological and mechanical strength of composite hydrogels or, on the other hand, to impart special properties such as biological activity and thermal stability.

Thus, there is growing interest in finding sustainable and safe cross-linking choices based on natural moieties. For example, it is known [5], that mixtures of proteins with polysaccharides can give variety of phase behavior with synergistic or antagonistic effects creation of soluble or insoluble complexes. One of the most promising materials for this purpose is SA [6]. SA is a water-soluble, neutral and linear polysaccharide with non-toxic, biocompatible, biodegradable and non-immunogenic properties, due to which SA has found use in various biomedical applications, among which the most promising are drug delivery and gene delivery [5], wound dressing [8] and wound healing [9]. According to Cao et al. [10], alginates are natural polysaccharides isolated from brown seaweeds and certain bacteria. SA is an alginic acid derivative consisting of 1,4-β-d-mannuronic (M) and α-l-guluronic (G) acids linked by glycosidic bonds (1$\rightarrow$4), and has the chemical formula $(NaC_6H_7O_6)n$ [9]. The structure of the alginate is formed either by homopolymer (MM or GG) or heteropolymer (MG or GM) blocks. The negative charge of alginate is provided by carboxyl groups (one per monomer) [9]. Pure solutions of SA did not exhibit temperature effects [5]. However, alginates are capable of forming hydrogels through ionotropic gelation with divalent or multivalent cations, and the most studied system is ionotropic gelation with calcium cations, usually described using the “egg box” model [9], which assumes two antiparallel polyuronate chains that form egg-box dimers with Ca^2+ and further aggregate laterally to form multimers. Alginates are also capable of gelation with transition metal cations such as Co^2+, Ni^2+,Cu^2+ and Fe^2+ [8], due to their ionic cross-linking in the presence of divalent cations. Ursini et al. [9] described the formation of metal-free alginate hydrogels in the presence of the free organic amino acid glutamine, when the protonated amino acid causes a shielding effect for electrostatic repulsion of alginate chains, which leads to the formation of chain cross-links and chain–chain stabilization. Disadvantages of SA include its low mechanical strength and cell adhesion, low level of drug loading, hydrophilicity, microbial degradation and burst release [4]. According to Ahmad et al. [4], to overcome such problems, SA should be mixed with various types of synthetic or natural polymers, which would improve its properties.

Recently, many studies have been devoted to the formation of alginate-GN complexes in GN-SA-H_2O systems, which demonstrate the joint synergistic effect of alginate and GN on the rheological and thermo-responsive properties of complex hydrogels [5]. Venezia et al. [5] studied intermolecular electrostatic interactions and hydrogen bonds, as well as, to a lesser extent, hydrophobic interactions between macromolecular chains of GN and SA with the formation of polyelectrolyte complexes in aqueous solutions. Complexation in GN-SA-H_2O systems is accompanied by a change in the secondary structure of GN. As reported by Derkach et al. [7], at a low mass ratio of polysaccharide to GN (up to 0.2), a decrease in the proportion of collagen-like helices and an increase in the share of random coil conformation of GN chains is shown. According to Venezia et al. [5], aqueous solutions of SA with a high content of GN at temperatures below 36°C contained rod-shaped structures that were considered as the initial stage of the helix-coil transition. These gels were prepared at the ratio GN to alginate 2:1; their thermoreversible behavior indicates the absence of covalent cross-linking during gelation in binary mixtures GN-SA-H_2O [5]. As a result of electrostatic interactions, hydrogen bonds and hydrophobic interactions between alginate and GN, the characteristic temperatures of the gel-sol and sol-gel transitions were shifted towards higher values. For example, in thermo-responsive hydrogels of the GN-SA-H_2O system with 5 %wt. GN and 5 %wt. SA, the gelation temperature

Tg increased to 27.3 °C, and the melting temperature Tm increased to 35.9 °C [5].

1.3. Humic acids in thermo-responsive biopolymer hydrogels

In order to increase Tm to a physiological temperature of 37 °C, it was necessary to introduce an additional cross-linking agent into the GN-SA-H_2O system, which, at the same time, did not interfere with the thermoreversibility of the GN-alginate hydrogel [2]. In [5], the addition of humic acids (HAs) was used as a way to tune the gelation of GN hydrogels. Among the bioavailable compounds, HAs are an alkali-soluble fractions obtained as a result of oxidative destruction biomass in natural or biorefinery processes, which contain fragments with different functionality in their main chains including quinone, phenol, carboxyl and hydroxyl groups that give them various properties such as antioxidant, antibacterial and anti-inflammatory activity [11]. De Melo et al. [11] indicate that quinones are responsible for the formation of reactive oxygen species in HAs, which are beneficial for wound healing and have fungicidal/bactericidal properties. Phenols and carboxylic acids are deprotonated in neutral and alkaline environments and are responsible for various other functions, such as the antioxidant and anti-inflammatory properties of HAs. In particular, the presence of phenolic groups in HAs provides antioxidant properties due to their ability to scavenge free radicals. HAs are the most studied group of humic substances, which are natural non-toxic complexing ligands found in nature [12]. In turn, humic substances make up the main part of organic matter [13], since they represent most of the organic materials of soil [14], peat, lignites, brown coals, sewage, natural waters and their sediments [15].

Thus, HAs are biological wastes found in nature in large quantities [5]. The chemical composition and properties of HAs may vary depending on geographic location, origin, age, climate and biological conditions, making it difficult to accurately characterize these substances. In particular, the molecular weights of HAs vary in the range from 2.0 to 1300 kg/mol [15]. According to the currently generally accepted opinion [5], HAs consist of relatively low molecular weight compounds (2-150 kg/mol) that are self-organizing into supramolecular structures held together by weak dispersion forces such as Van der Waals, π-π and CH-π interactions. Moreover, due to the non-covalent nature of the stabilizing interactions, HAs superstructures are not only highly dependent on environmental chemistry, including pH and associated biological molecules, and behave as dynamic systems, but are also subject to self-restructuring in water [5]. Commercial HAs are extracted from peat and lignites in the form of a fraction that is soluble in alkali, but insoluble upon subsequent acidification [5]. The inclusion of HAs in the GN network in [5] influenced viscoelastic properties as well as thermal stability the resulting GN-HAs-H_2O gel. Aldrich HAs was chosen in [5] as a model HAs fragment to study the gelation kinetics and transition temperatures depending on the HAs concentration in thermo-responsive GN-HAs-H_2O hydrogels with HAs/GN concentrations changed in the range 2.67-26.67 wt./wt. Research by Venezia et al. [5] has shown that at lower concentrations of HAs/GN (up to 13.33 wt./wt.). HAs improve the thermal properties of the resulting GN-HAs-H_2O gels due to tight physical interactions of HAs with GN. The melting temperatures Tm of these hydrogels were increased to 33°C at a ramp rate of 1°C/min and to 35°C at a ramp rate of 10°C/min; the corresponding Tg values were 24°C and 16°C, respectively [5]. According to Venezia et al. [5], since HAs are organized into supramolecular soft and permeable clusters exposing hydrophilic groups, while hydrophobic particles are shielded in the interior, these chemical features make HAs highly reactive with proteins. Accordingly, they can interact with GN through non-covalent interactions such as hydrophobic and electrostatic interactions, as well as through H-bonds. Notably, H-bond interactions must be established between the carbonyl groups of HA and the hydroxyl groups of hydroxyproline and proline residues, as well as amino moieties of glycine, which are the most abundant amino acids in GN chains [5]. Thus, up to a maximum concentration of GN and HAS of 13.33 wt./wt., HAs have a beneficial effect on the gelation process, promoting the formation of a denser network. However, higher concentrations of HAs in the GN-HAs-H_2O system led to a disordered structure with a random coil organization of GN, since HAs, due to their high affinity for water, establish preferential bonds with water molecules, preventing them from being coordinated with GN chains [5]. Since water plays a key role in stabilizing the triple helix structure and the resulting gel network, being able to act as a link between GN chains due to H-bonds, at high HAs content the secondary structure of GN lost its triple helix structure. In addition, the content of HAs more than 13.3 %wt. causes swelling phenomena due to water absorption of HAs, which promotes the formation of a weaker gel with reduced thermal stability, and also causes partial coagulation of the protein with the formation of aggregates and precipitation phenomenon, which can prevent the return of GN chains to the ternary structure spirals [5]. Therefore, the melting temperatures Tm of hydrogels in the GN-HAs-H_2O system with HAs/GN concentrations 26.67 wt./wt. were decreased to 26°C at a ramp rate of 1°C/min and to 29°C at a ramp rate of 10°C/min; their Tg values were 17°C at a ramp rate of 1°C/min and 9°C at a ramp rate of 5°C/min [5].

Thus, all thermo-responsive hydrogels based on the GN-SA-H2O and GN-HAs-H_2O systems developed to date have melting points below the physiological temperature of 37°C. Considering the relevance of creating a biocompatible thermo-responsive hydrogels with a physiological melting point based on non-toxic and available biomaterials that have wound-healing properties and are suitable for controlled drug delivery, in this work we developed and studied a more complex GN-SA-HAs-H_2O system. This article has the following objectives. First, it is the optimization of the compositions of thermo-responsive biologically active GN-alginate hydrogels by studying their rheological properties using the viscosimetric method in order to adjust the melting temperature to physiological conditions. Secondly, the aim of this work is to modify thermo-responsive bioactive GN-alginate hydrogels with HAs, which have antioxidant, antibacterial and anti-inflammatory activities, to provide a concrete chance for technological application of HAs in accordance with the "waste-to-wealth" approach. Thirdly, it is assessment of the temporal conditions of the gel-sol transition of thermo-responsive bioactive GN-alginate hydrogels modified by HAs with physiological melting point, and the characterization of these thermo-responsive GN-SA-HAs-H_2O hydrogels using Fourier transform infrared spectroscopy (FTIR).

2. Materials and methods
In this work, food GN brand R-11 was purchased in Ukraine, and SA in the form of sodium salt of alginic acid was purchased in China.

2.1. Preparation of humic acids and thermo-responsive hydrogels
A solution of HAs with a concentration of 8.5 %wt. NaOH in the form of a nanodispersion with a nanoparticle size in the range of 52 – 380 nm was obtained by extraction of lignite with a solution of sodium pyrophosphate, and further extraction with 1%wt. sodium hydroxide and precipitation with mineral acid. To obtain HAs, a 10–15 g sample of lignite was first crushed to a particle size of less than 1 mm. The crushed lignite sample was then extracted with toluene with a density of 0.867 g/cm^3.

After extraction, it was air dried and further ground to a particle size of less than 0.2 mm. Then, the sample weighing 1 g or 2 g in terms of dry ash-free mass was transferred to a conical flask A with a volume of 250 ml, to which 100 ml of an alkaline solution of sodium pyrophosphate was added, and the resulting solution was stirred for 1 hour with a mechanical shaker. The obtained suspension was centrifuged for 15 min at 210 rotate per second. The solution was decanted, collecting in a conical flask B with a capacity of 1000 ml. The residue that did not dissolve was rinsed twice with 100 ml of sodium hydroxide solution. The suspension was centrifuged after each rinse, collecting the rinsing solution in flask B. The rinsed residue was transferred to flask A, 100 ml of sodium hydroxide solution was added and heated for 2 hours in a water bath. After cooling to room temperature, the content of flask A was centrifuged for 15 min at 210 rotate per second. The solution was decanted and collected in flask B. The residue, which did not dissolve, was rinsed twice with the use of 100 ml of sodium hydroxide solution. The suspension was centrifuged after each rinsing, collecting the rinsing solution in flask B. Extraction of HAs was carried out for 7 hours. The contents of flask B were filtered into a 1000 ml flask, and water was added until the whole volume was 1000 ml. Then, 100 ml of the filtrate was collected with a pipette and transferred to a beaker, and 60 ml of 5 % vol. hydrochloric acid was added to precipitate HAs. The suspension was centrifuged. After centrifugation, the solution was separated by decantation and the HAs precipitate was rinsed with water. Rinsing the sediment led to the beginning of peptization of HAs, which was determined by the appearance of a weak yellow color (colloid formation). After that, 5 ml of 5 %vol. hydrochloric acid was added to this colloidal solution for additional precipitation of HAs. The sediment of HAs was filtered through an ash-free filter, which was previously dried to a stable mass in a drying oven at 90±5°C. The filter with the sediment of HAs was placed in an aluminum weighing bottle, previously dried to a stable mass in an oven at 90±5°C, and dried at a temperature of 90±5°C for 1 hour. The bottle with contents was then removed from the drying oven, cooled for 5 minutes in air, and then additionally dried in a desiccator. Control cooling and drying were repeated until the difference in mass of the two subsequent samples was less than 0.001 g.

Subtracting the mass of the weighing bottle and filter, the mass of the HAs-containing sediment was determined. Finally, the dried filter with the HAs-containing sediment was transferred to the pre-frying crucible in a muffle furnace at a temperature of 600±25°C for 1-2 hours until it was solidified and its mass was stabilized. Then the crucible was removed out of the muffle furnace, cooled and dried for 5 hours in air, and then dried in a desiccator with a drying agent. Control frying at the same temperature for 15 minutes, cooling and drying were repeated until the difference in mass between the two subsequent experiments did not exceed 0.001 g. The mass of HAs was determined by subtracting the mass of the crucible.

To obtain thermo-responsive hydrogels GN-SA-H_2O and GN-SA-HAs-H_2O, a certain amount of GN was first placed in distilled water preheated to 90 ± 2°C and stirred on a VEVOR 85-2 magnetic stirrer with a heating plate until a pure GN sol was obtained. To prepare a GN-alginate hydrogel, SA was added to a previously prepared GN sol and stirred with a VEVOR 85-2 magnetic stirrer with a heating plate until a homogeneous sol GN-SA-H_2O was obtained. In this work, we used GN-SA-H_2O systems contained 14 %wt. GN and 3.2 %wt., 6.4 %wt. or 9.6 %wt. SA. To prepare GN-SA-HAs-H_2O systems, HAs were added to the GN-alginate hydrogel, containing 14 w%wt. GN and 6.4 %wt. SA, at concentrations of 2.5 %wt.HAs, 5 %wt. HAs or 7.5 %wt. HAs.

2.2. Characterization

Herein, to optimize the composition of thermo-responsive hydrogels, a standard method for determining kinematic viscosity (mm^2/s) was applied using a glass viscometer VPZh-2 3.35 with a capillary diameter of 3.35 mm and a viscometer constant of 10. Measurement of kinematic viscosity using a viscometer VPZh-2 based on determining the time of flow of a certain volume of sol through a capillary from a measuring container. The gel-sol transition temperature Tm was recorded from the onset of free flow of the sol through a widening in a capillary with a diameter of 3.35 mm.

The technique for studying the gel-sol transition time of thermo-responsive bioactive hydrogels of the GN-SA-H2O and GN-SA-HAs-H2O systems included visual observation and determination of the time of softening and subsequent melting of hydrogel washers 1 cm high and 1.5 cm in diameter, located on glass substrate heated to a physiological temperature of 37°C, which confirmed the gel-sol transition process. Fourier transform infrared spectroscopy FTIR has been used to study non-covalent interactions between GN, SA and HAs in these thermosensitive bioactive hydrogels with a physiological melting point. FTIR spectra were taken using an IR spectrophotometer Nicolet 380 (USA) at 20-25 °C in the 4000-500 cm^{-1} frequency range.

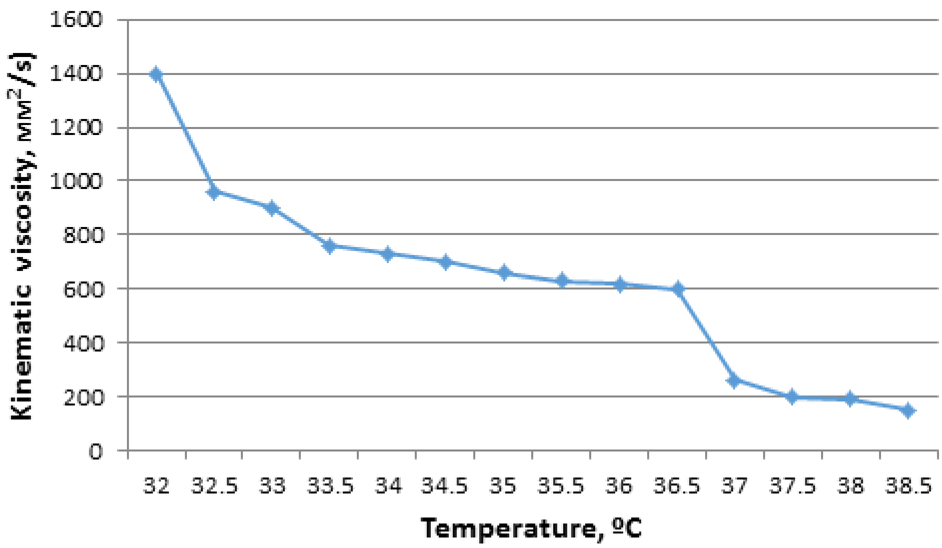

Figure 1. Rheological studies of a thermo-responsive bioactive hydrogel containing 14 %wt. GN and 6.4 %wt. SA

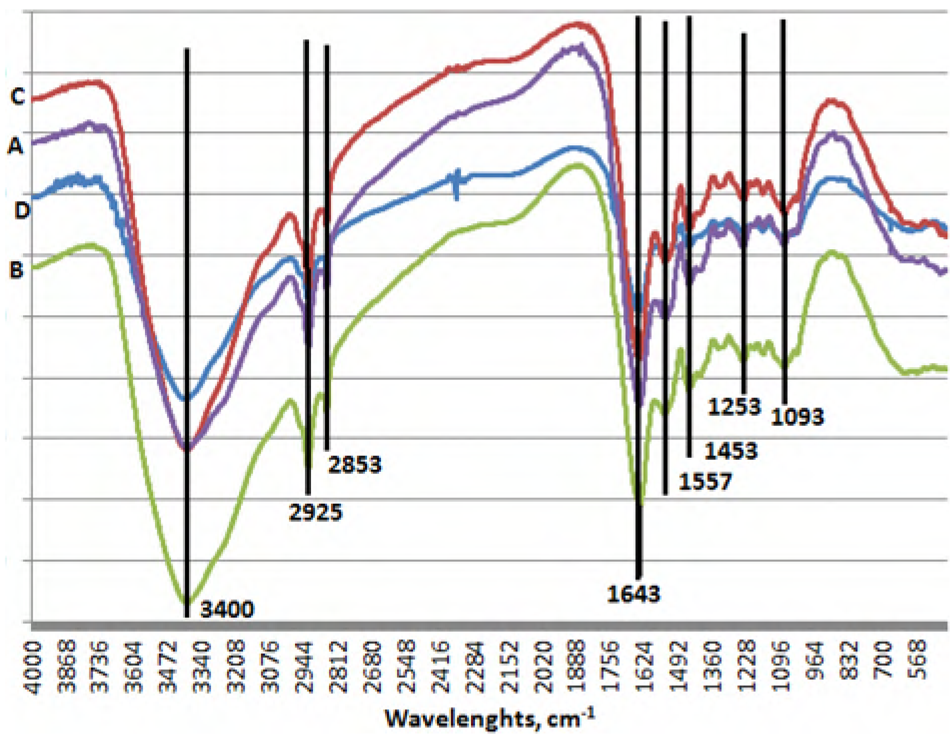

Figure 2. FTIR spectra of the developed thermo-responsive bioactive GN-alginate hydrogel containing 6.4 %wt. SA and 14 %wt. GN (A), and this GN-alginate hydrogel modified with HAs: 2.5 %wt. HAs (B); 5 %wt. HAs (C); 7.5 %wt.HAs (D)

3. Results and discussion

Based on the data by Goudoulas and Germann [6], that in a thermo-responsive hydrogel of the GN-SA-H_2O system with 5 %wt. GN and 5 %wt. SA the melting point Tm is 35.9°C, it was decided to enhance the thermal stability of the GN-alginate hydrogel and thereby bring Tm closer to the physiological level of 37°C by increasing the concentration of its components. When choosing the concentration of GN, we proceeded from the information [6] that at concentrations of more than 13 %wt. GN and temperatures below 40°C, GN chains undergo a progressive conformational change from coil to helix, forming networks of triple helices. Thus, the thermo-responsive hydrogels, the rheological studies of which were carried out, contained 14 %wt. GN and different concentrations of SA: 3.2 %wt., 6.4 %wt. or 9.6 %wt. SA. Experimental studies showed that for a hydrogel containing 14 %wt. GN and 3.2 %wt. SA, the formation of a stable

Table 1. Infrared spectral characteristics of the amide structure developed thermos-responsive bioactive GN-alginate hydrogels containing 6.4 %wt. SA and 14%wt. GN, including those modified with HAs, in comparison with literature data.

Region	System	Band in cm^{-1}	Band assignment
Amide A	GN-H_2O [7]	3306	υNH, υOH
	SA-H_2O [7]	3420	υOH
	GN-HAs-H_2O [5].	3430	υNH, υOH
	GN-SA-$H_2O$and GN-SA-HAs-H_2O*	3400	υNH, υOH
Amide B	GN-H_2O [7]	2960–2935	asym and sym υCH_2
	GN-HAs-H_2O [7]	2930	asym υCH_2
	GN-SA-$H_2O$and GN-SA-HAs-H_2O*	2925, 2853	asym and sym υCH_2
Amide I	GN-H_2O [7]	1653	υC-O, υC-N
	GN-HAs-H_2O	1650	υC-O, υC-N
	GN-SA-$H_2O$and GN-SA-HAs-H_2O*	1643	υC-O, υC-N
Amide II	GN-H_2O [7]	1541;1400	δ NH, υC-N;sym υCOO-
	GN-HAs-H_2O [7]	1540;1450	υNH, υC-N, υC-C; υCH_2
	GN-SA-$H_2O$and GN-SA-HAs-H_2O*	1557;1453	δ NH, υC-N;sym υCOO-
Amide III	GN-H_2O [7]	1238	δ NH,υCN
	GN-HAs-H_2O [7]	1235	δ NH,υCN
	GN-SA-$H_2O$and GN-SA-HAs-H_2O*	1253	δ NH, υCN

* in this work

Table 2. Infrared spectral characteristics of the saccharide and HAs structure developed thermos-responsive bioactive GN-alginate hydrogels containing 6.4 %wt. SA and 14%wt. GN, including those modified with HAs, in comparison with literature data.

Region	System	Band in cm^{-1}	Band assignment
Saccharide	SA-H_2O [7]	1092	υC-O mannuronic
	GN-SA-$H_2O$and GN-SA-HAs-H_2O*	1093	υC-O mannuronic
HAs	GN-HAs-H_2O [7]	3390	phenolic OH
		2925	aliphatic CH
	GN-SA-HAs-H_2O*	3400	phenolic OH
		2925	aliphatic CH

* in this work

sol flow was not observed over the entire range of kinematic viscosity studies. A hydrogel with an increased content of SA, containing 14 %wt. GN and 9.6 %wt. SA, had a Tm near 71 $^{\circ}$C, and the formation of its stable sol flow was not observed in kinematic viscosity studies. According to Hernández, Sacristán and Mijangos [8], this behavior can be explained by the presence of a larger number of polymer chains responsible for more entangled bonds, and is typical for chemical gels that are covalently cross-linked and, therefore, do not melt, i.e., they are not thermo-responsive hydrogels. As can be clearly seen from figure 1, according to rheological studies, a hydrogel containing 14 %wt. GN and 6.4 %wt. SA is thermo-responsive and has a gel-sol transition, manifested in a sharp decrease in its kinematic viscosity at a physiological temperature of 37°C.

According to Venezia et al. [5] and based on data from our previous works [16, 17], which showed enhanced mechanical and transdermal characteristics of biopolymer GN hydrogels modified with HAs, in this work we added HAs to the developed thermo-responsive bioactive GN-alginate hydrogel, containing 6.4 %wt. SA and 14 %wt.GN. Analysis of the obtained hydrogels of the GN-SA-H_2O and GN-SA-HAs-H_2O systems by Fourier transform infrared spectroscopy is presented in figure 2. Tables 1, 2 shows their infrared spectral characteristics in comparison with literature data for GN hydrogel [6], for alginate hydrogel [7], and for the GN-HAs-H_2O system [5]. Absorption bands in the FTIR spectra in figure 2 are listed in table 1 to stretching

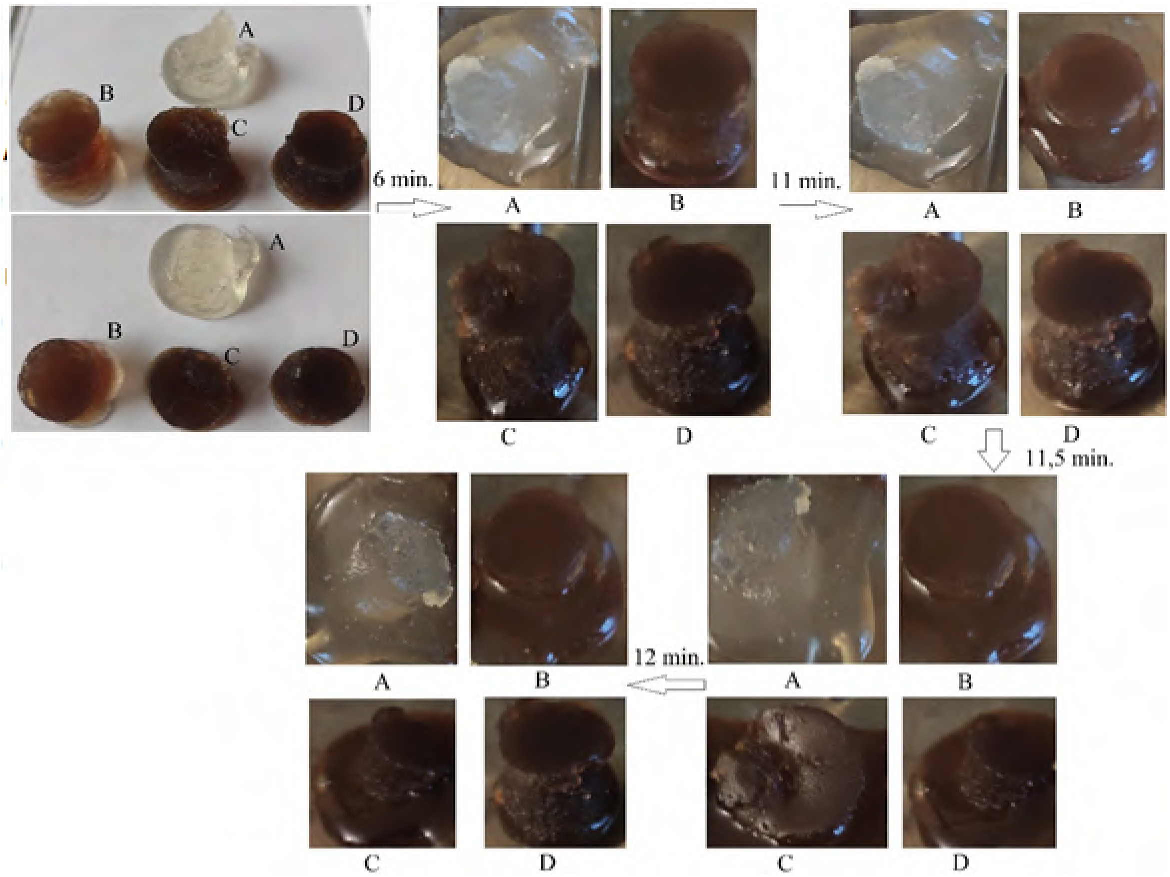

Figure 3. Photos to visually demonstrate the results of a study of the gel-sol transition time at a physiological temperature of 37°C for samples of the developed thermo-responsive bioactive GN-alginate hydrogel containing 6.4 %wt. SA and 14 %wt. GN (A), and for this hydrogel modified with different contents of HAs: 2.5 %wt. HAs (B); 5 %wt. HAs (C); 7.5 %wt. HAs (D).

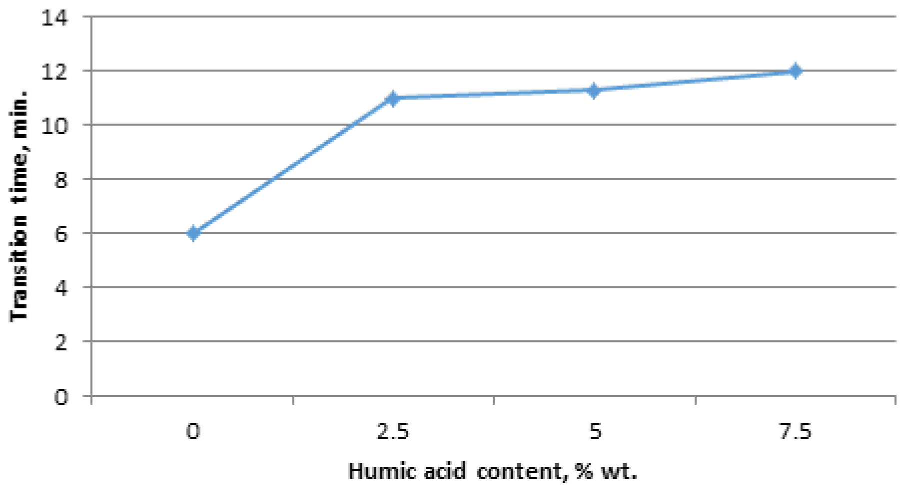

Figure 4. Graph of the gel-sol transition time at a temperature of 37°C in the developed thermo-responsive bioactive GN-alginate hydrogel containing 6.4 %wt. SA and 14 %wt. GN from the concentration of HAs in it.

υ and bending δ vibrations of the corresponding functional groups based on literature data for GN, SA and HAs [12]. It can be seen that the FTIR spectra of the GN-SA-H_2O and GN-SA-HAs-H_2O systems are similar. Small red and blue shifts in the positions of stretching and bending vibrations occurred due to GN-SA, GN-HA and SA-HA interactions similar to those observed in [5], in particular due to a conformational change in the secondary structure of GN.

Figure 3 presents visually results of a study of the gel-sol transition time at a physiological temperature of 37°C for samples of the developed thermo-responsive bioactive GN-alginate hydrogel containing 6.4 %wt. SA and 14 %wt. GN, and also samples of this hydrogel modified with different contents of HAs. Figure 4 shows a graph of the dependence of the gel-sol transition time at a temperature of 37°C on the concentration of HAs in this hydrogel.

A sharp increase in transition time from 6 min to 11 min can be seen as a result of adding 2.5 %wt. HAs to the termo-responsive GN-alginate hydrogel at 37°C. Further increasing the HAs content in the hydrogel to 5 %wt. HAs and 7.5 %wt. HAs led to a slight increase in the gel-sol transition time to 11.5 min and 12 min, respectively. Thus, these studies showed that relatively small concentrations of HAs can provide a prolonged effect of drug delivery through the use of GN-alginate hydrogel on the surface of the human body.

4. Conclusions

In this work, we developed hydrogel systems that synergistically combined the outstanding properties of natural molecular polymers GN and SA, such as low cost, nontoxicity, biocompatibility, biodegradability, and non-immunogenicity. In addition, using our own technology, HAs with antioxidant, antibacterial and anti-inflammatory activity were obtained from lignite and added to GN-alginate hydrogel, which provided a concrete chance for the technological use of HAs in accordance with the "waste-to-wealth" approach. Rheological studies confirmed that the hydrogel containing 14 %wt. GN and 6.4 %wt. SA is thermo-responsive and has a gel-sol transition, manifested in a sharp decrease in its kinematic viscosity at a physiological temperature of 37°C. The FTIR spectra of the GN-SA-H_2O and GN-SA-HAs-H_2O systems are similar. The small red and blue shifts in stretching and bending vibration positions occurred due to GN-SA, GN-GA, and SA-GA interactions are similar to those observed in the literature, in particular due to a conformational change in the secondary structure of GN. The results of a study of the gel-sol transition time at a physiological temperature of 37°C for samples of the developed thermo-responsive bioactive GN-alginate hydrogel containing 6.4 %wt. SA and 14 %wt. GN, as well as samples of this hydrogel modified with different contents of HAs, visually showed a sharp increase in the gel-sol transition time from 6 min to 11 min as a result of adding 2.5 %wt. HAs. Thus, the studies have shown that GN-alginate hydrogel, modified with relatively small concentrations of HAs, is capable of providing a prolonged effect of drug delivery when it is located on the surface of the human body.

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Development of the modeling system core for severe plastic deformation processes

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Development of the modeling system core for severe plastic deformation processes

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Abstract. The research is focused on the development of the structure of the core of the integrated automated modeling system (AMS). The AMS ensures an increase in the functionality of the CAD and CAE systems by combining them with several external independent modules. The AMS modeling technological schemes of severe plastic deformation processes, the behavior of materials in deformation processes, and reducing the cost of choosing the scheme and parameters of the deformation processes. Object-oriented software was developed to analyze the influence of different initial shapes of the billets and the die sets on the changes in the billet's cross-section during deformation. The software is written in C# using the WPF interface and the page structure of the main application window. Using parametric models of processes enables automated calculations in CAE systems and the generation of 3D geometric models of die sets in CAD systems. The design of experiments allows automation research of severe plastic deformation (SPD) processes and reduces the costs of studies. Importing and accumulating calculation results in the CAE system made it possible to find the optimal values of the parameters of SPD technological processes. The parameters of the deformation models obtained based on modeling are the basis for constructing the geometry of the die set in CAD with subsequent integration with CAE to calculate the stress-strain state in the volume of the billet. Ways to expand software functions to support various SPD processes are proposed.

1. Introduction

The processes of severe plastic deformation (SPD) make it possible to obtain materials with a fine-grained structure and improved physical and mechanical properties. SPD processes have been actively developing in recent years, but their research and implementation in industry are more difficult than classical processes of metal forming (MF). Despite the difficulties in obtaining such materials, they are needed in aircraft construction, automobile construction, medicine, and other high-tech industries. Modern integrated AMS (iAMS) systems based on industrial CAD/CAE systems do not allow high-quality modeling of multi-stage technological processes of SPD. This is due to the limited capabilities of integrated AMS, particularly CAE systems, for implementing user models of the behavior of new materials, solving the problems of analyzing the modeling results, and optimizing the SPD processes. When modeling technological processes of MF [1,2], and especially SPD processes, it is necessary to automate the movement of the billet in the space between technological operations and positioning relative to the tool when using their parametric models while preserving the parameters of the stress-strain state between operations, as well as when changing the deforming tool. This is important because when automating tool change, the possibility of structural optimization is realized for the selection of deformation routes using various operations.

Automation of the design of new technological processes includes the stages of developing a conceptual model, a geometric model, and determining process parameters [3–6]. Therefore, in order to automate the formulation of the problem, a method of creating a calculation model template is proposed: to change the corresponding models or calculation parameters in the CAE system using software testing tools (IBM Rational Functional Tester, Unified Functional Testing, TestComplete, etc.) or in manual mode. After entering the parameters of the SPD process modeling in the corresponding CAE system, the user receives the SPD calculation model for the specified geometric model.

Computer-aided engineering (CAE) are used to model physical processes in various branches of mechanical engineering and metallurgy and to significantly speed up the process of designing structures of any complexity without conducting time-consuming experiments. Such systems are widely used in production and scientific research in the field of modeling processes of MF. CAE systems provide opportunities for modeling a wide range of MF processes, starting from sheet forming operations and ending with volumetric stamping or rolling operations, at different temperature modes, with loads, etc. They allow engineers and technologists to see the process of shape change of billets, as well as to investigate the stress-strain state of the processed billets and the tool. Such calculations are performed using universal CAE systems based on the finite element method (FEM) [7, 8], such as Ansys, LS-Dyna, HyperWorks, ABAQUS, QForm 3D [9–14], etc. In such CAE systems, explicit solvers for the calculation of nonlinear processes are implemented [15], which allows modeling the shape change of the billet at large degrees of accumulated deformation and the use of rheological models of the plastic flow of the billet metal. For several MF operations, the obtained shape of the billet is of primary importance, and the stress-strain state is less important. Specialized CAE systems focused only on MF processes are widely used in production.

Currently, various CAD systems have been developed for the design of individual processes (groups of typical processes) of MF, which allow to reduce the time for preparing the calculation in the CAE system. For the SPD equal-channel angular extrusion (ECAE) and twist extrusion (TE) processes, CAD was developed for designing the technological process based on a set of initial data [16, 17]. For less common SPD processes, such CAD does not exist.

2. Development of the designing processes in procurement production

When simulating SPD processes, additional problems arise related to the features of the process itself: the need to simulate various variants of billet loading schemes, large plastic deformations, changes in deformation routing, thermal mode, etc. A feature of SPD processes is that at each subsequent deformation operation, the position of the billet changes due to its rotation around one or two axes in space, which ultimately ensures the uniformity of the distribution of properties over the volume of the billet. Building a model of the SPD process, which includes 4-5 deformation operations with constant movement of the tool and rotations of the billet, requires the construction of a model for the CAE system, which for 1 deformation operation will include 2-3 auxiliary steps in which exactly the rotation of the billet and movement of the tool takes place to new provisions. Thus, the calculation model in the CAE system for the SPD process with 4-5 deformation operations includes 12-15 modeling steps, while deformation in classic MF operations is performed in 1-3 modeling steps. Manual preparation and adjustment of such a complex model takes a lot of the researcher's time. Automating the construction of such models will allow you to get a working model on the first try with little adjustment.

To date, the problems of computational complexity in modeling plastic deformation processes, which are labor-intensive and require significant expenditure of machine time, remain unsolved. The use of parametric models to perform optimization calculations additionally leads to a large number of calculation cycles, which in some cases makes such a modeling scheme inefficient.

The purpose of the research: improve the quality of integration of CAD/CAE systems and develop the functionality of iAMS based on the creation of an object-oriented core for combining external independent modules that provide flexible and adequate modeling of multi-stage SPD processes using parametric models.

3. Structure and functionality of the integrated AMS core

To solve several tasks in the design of SPD processes and the development of iAMS functionality, it is necessary to develop a core that should provide the possibility of modeling multi-stage combined SPD processes; support the integration of external modules with modern CAD (SolidWorks) and CAE (Abaqus, QForm) for modeling stress-strain state of billets during deformation; to provide research into the technological possibilities of new SPD processes based on the parameterization of models of billets and die sets [18].

Based on the analysis of the capabilities of CAD/CAE systems, the functions that should support the core of integrated AMS and the necessary mechanisms for this are highlighted:

- to maintain a data structure for organizing a set of modules;
- to provide a flexible exchange of information between system modules, which can be configured;
- to ensure the preservation of the system state in the form of a collection of objects that contain the parameters of this state;
- the iAMS core should support saving the state parameters for the executed project in (XML) format and restoring the system state parameters for the selected project upon loading. If necessary, store meta-information about modules;
- to ensure the connection of external modules with a low degree of connectivity;
- to provide the possibility of planning experiments in the form of a sequence of calculations with given initial parameters, for example, a List of objects in each module for saving data;
- to ensure the task of sequentially calling modules to perform the necessary sequence of calculations;
- to ensure the execution of optimization procedures, the setting of intervals for the variation of parameters that may change during the optimization process;
- performs general settings for iAMS, including the location paths of components and files necessary for operation.

The physical model of iAMS includes a number of typical external functional modules, which can be conditionally divided into two groups. Modules that solve system problems: connecting modules to organize interoperability, ensuring the selection of processes and routes for the next simulation, and integration with CAD/CAE systems. Modules for planning and carrying out experiments, as well as modules for directly solving the problems of modeling plastic deformation processes using SPD: creating a geometric model in the CAD system, modeling in the CAE system using parameterized scripts, and FEM.

Let's consider the areas of responsibility and functionality of the core classes of integrated AMS. The class diagram of the integrated AMS core is shown in figure 1, which presents the connections between classes of the core, which provides integration with functional modules (Module class) of the design system. This makes it possible to ensure the compatible operation of the system components for simulating the sequence of operations of the technological process specified by the user.

The main task of the kernel is to perform several system operations to ensure the joint operation of the functional modules of the system. The Core class includes a static collection of elements (Element) and thus provides modules access to information common to all. The kernel is also responsible for initializing the necessary modules at the start of the program. The Element

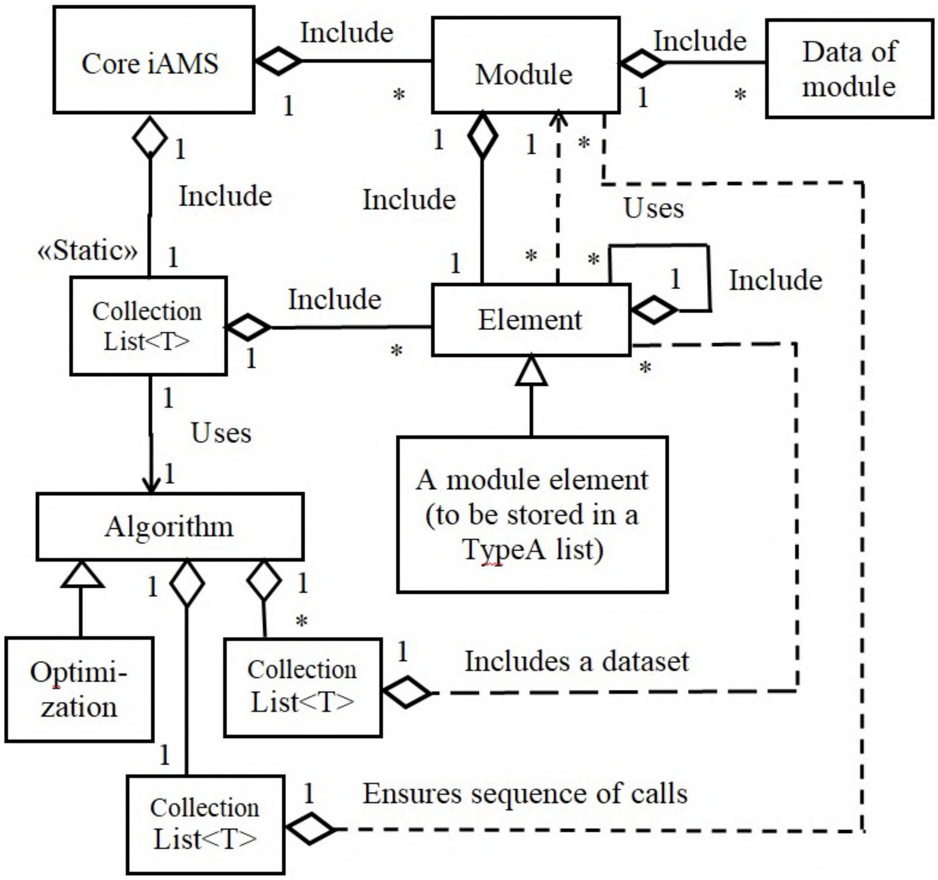

Figure 1. Class diagram of the core of the integrated AMS for designing SPD processes based on the development of a parametric model of billets and die sets.

base class includes a list of base class objects so that it is possible to prepare several options for output parameter tasks for each module, such as billets, fixtures, deformation conditions, etc, and store these settings in a file for later use.

Each module includes elements necessary for it and provides integration and use of external CAD/CAE and other systems. Each module has its own class system to ensure its operation depending on the purpose. For integration with the core, each module includes one inheritor object from the Element class. It contains data that is the result of the module's operation. These results may be necessary for the operation of other modules, as well as for presenting the results of the simulation as a whole. A class can also contain meta-information about the module to which it belongs. Another important responsibility of the system core is to save simulation results and output data to a file implemented in this project. The kernel provides the ability to restore the system state parameters that were saved and thus provides the initial configuration of the modules to continue the simulation. At the same time, a separate module ensures the setting of paths for access to files necessary for the work of other modules (not developed by the author of this work). AMS is implemented in C# in the MS Visual Studio environment using the WPF interface [19]. The main application window is built using a page structure that allows you to build AMS modules independently od them when needed. Each of the AMS modules is associated with its class.

Another responsibility of the system core is to ensure the planning of experiments using connected modules. For this, the Algorithm class was developed, which includes two collections of objects. One of them allows the user to choose the sequence of work performed by the system modules for a specific technological process, the second allows to select and form sets of initial data for each simulation experiment.

During operation, the algorithm sequentially transfers control and output information to the modules in a cycle, which in turn receives sets of output data for each experiment from the basic global list and performs their work.

After calculations in a specific experiment, the modules change the state of the data in a separate global list. After executing a given sequence of module calls, information about the state of the system (simulation results) is stored in a separate XML file, and then the work is repeated for a new set of output data.

4. Discussion

An important issue in conducting research is the planning of experiments. The interface of the module for planning the process of research on the modeling of the SPD process includes two elements of the ListBox type and a dynamically created table, as well as control elements of the Button type.

To plan experiments on the modeling of SPD processes, it is necessary to create lists of objects that contain variants of tasks, for example, several billets with different sizes, parametric models of equipment, etc. (figure 2, figure 3a).

Then, to study a specific technological process, the sequence of work with different modules is set. For this, when the module is activated, the entire set of modules is displayed in the interface. After that, the user selects the sequence that is required for the simulated process. When the Add button is pressed, the name of the modules selected by the user is displayed in the list. These modules are selected from the general list (figure 3a), which is shown in the

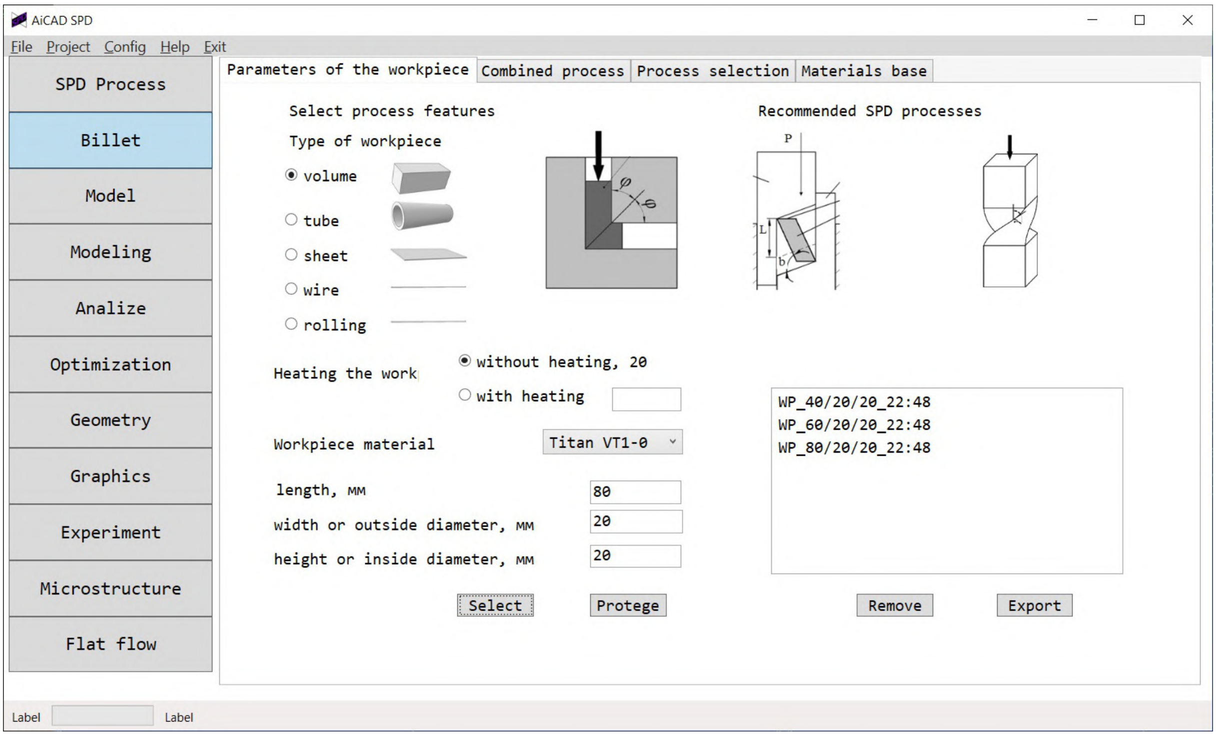

Figure 2. View of the user interface for working with the billet and process type selection module.

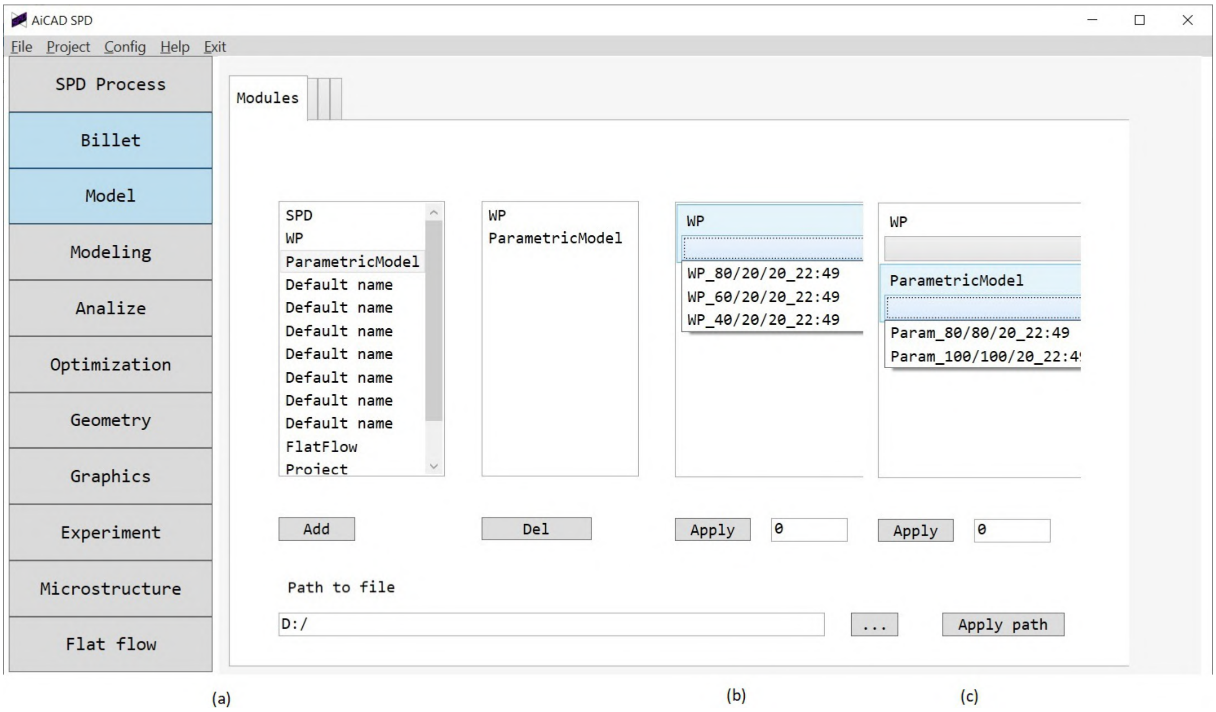

Figure 3. View of the user interface for working with the experiment planning module for the selected process.

left ListBox, and are displayed in the next ListBox (in the center). Lists of options for billets, equipment, and other previously created objects are displayed in the ComboBox included in the ListBox (right).

This list is subject to change. The display of pre-created lists of billets (see figure 3b) and equipment (see figure 3c) is provided in the ComboBox.

After checking the set of selected modules, you need to press the Apply button so that a list of experiment planning is dynamically generated for the applied modules (a table with the required number of terms). The columns of the table create the names of the modules (components) selected for operation.

In the table, each row corresponds to a separate modeling process. In the corresponding cells for each module, object indices are set, which contain the values of the initial parameters for modeling. By specifying objects with pre-prepared data in this way, you can successively fill rows in the table. After the planning of the simulation process is completed, a cycle of sequential activation of modules and execution of calculations takes place. Obtaining additional information from other modules and saving the results of their work is the responsibility of each module.

To simulate the selected technological process, the model is automatically built for the Abaqus CAE system. According to the parametric model of the technological process, a Python script is formed, which includes a set of Abaqus commands [20]. Interaction is implemented through the interface with the CAE Abaqus pre-processor. The Modeling module launches each model from the experiment plan to perform calculations (figure 4). As a result of modeling in Abaqus CAE, a file in .odb format is created for each process model, which is the internal format of Abaqus.

The import of simulation results is implemented in the Analysis module. A Python script is used to connect to the Abaqus post-processor. In the interface of the Analysis module, it is

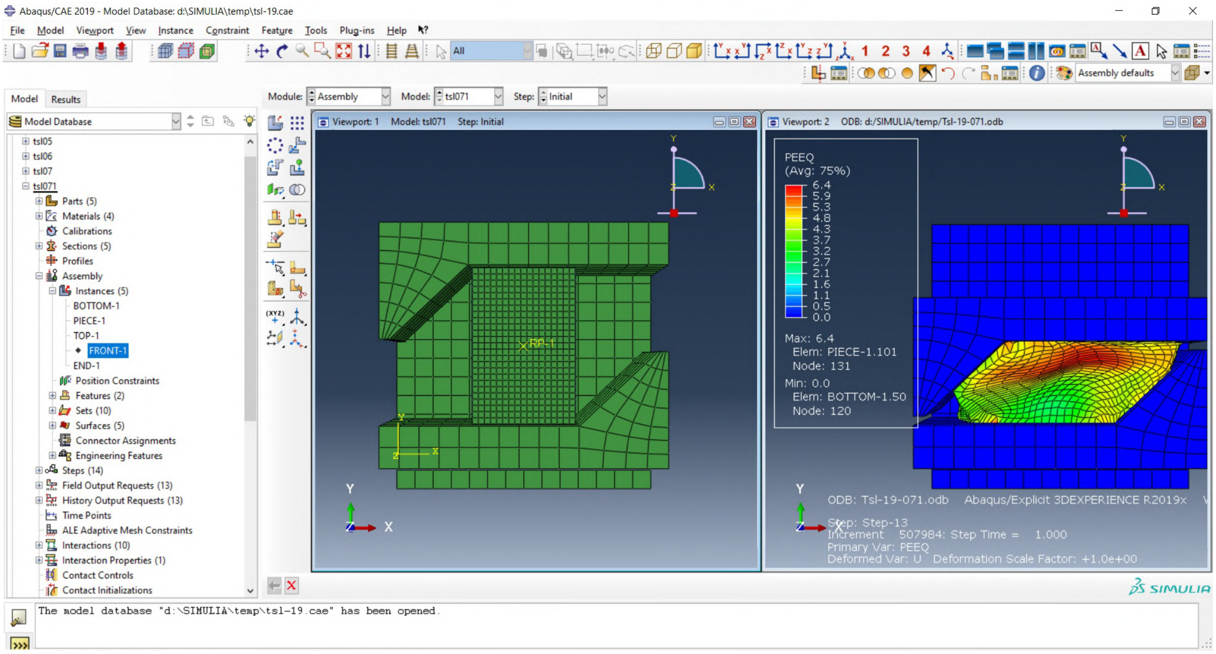

Figure 4. Model of the technological process in the Abaqus CAE system.

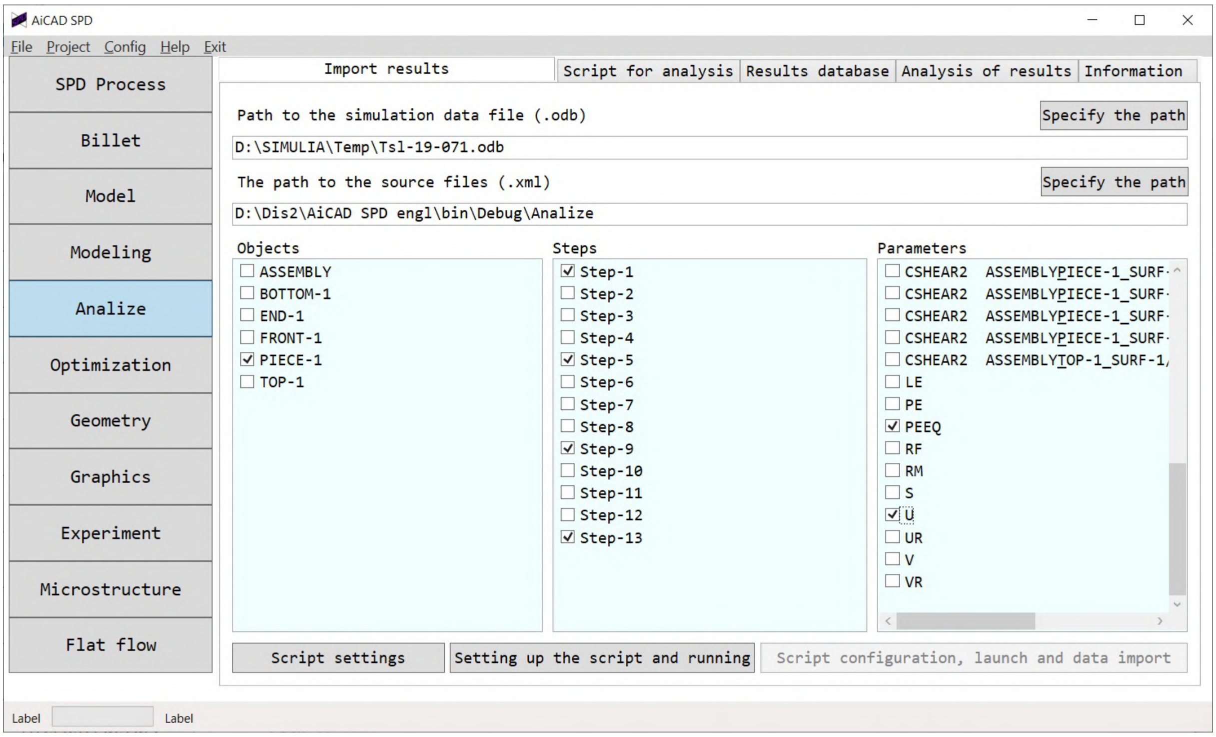

Figure 5. Interface for importing simulation results.

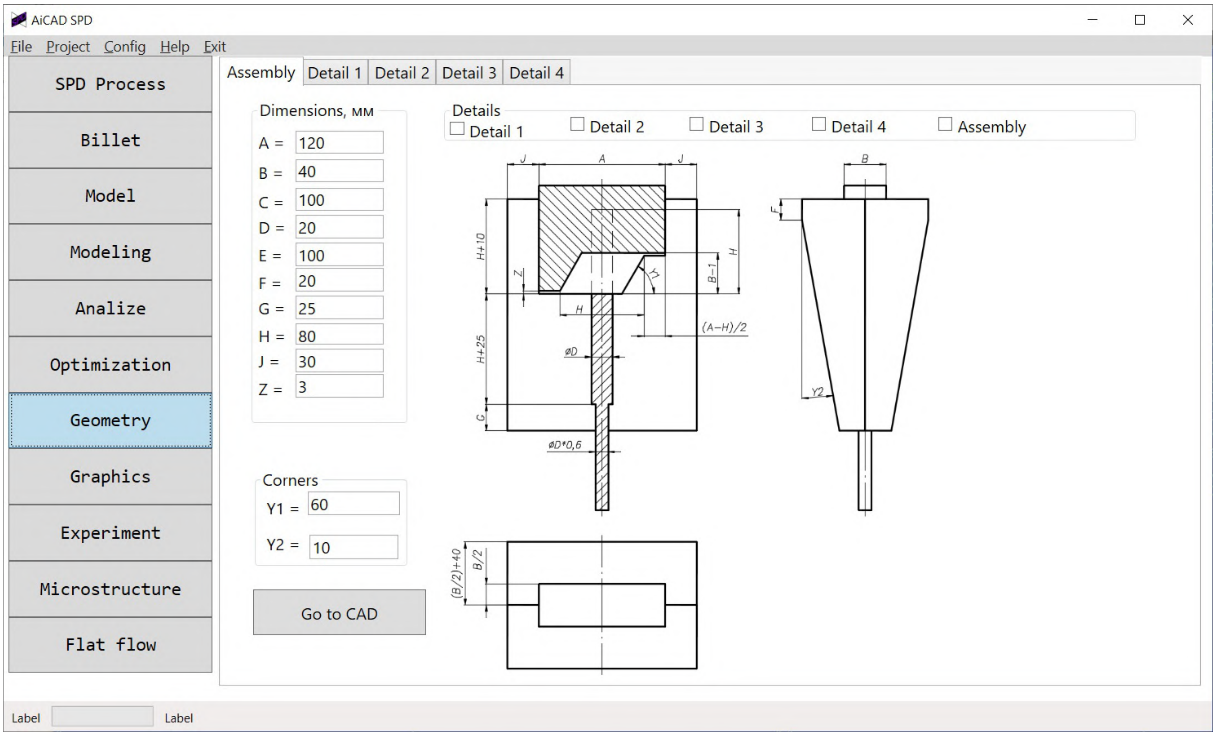

Figure 6. Construction of the geometry based on the parametric equipment model.

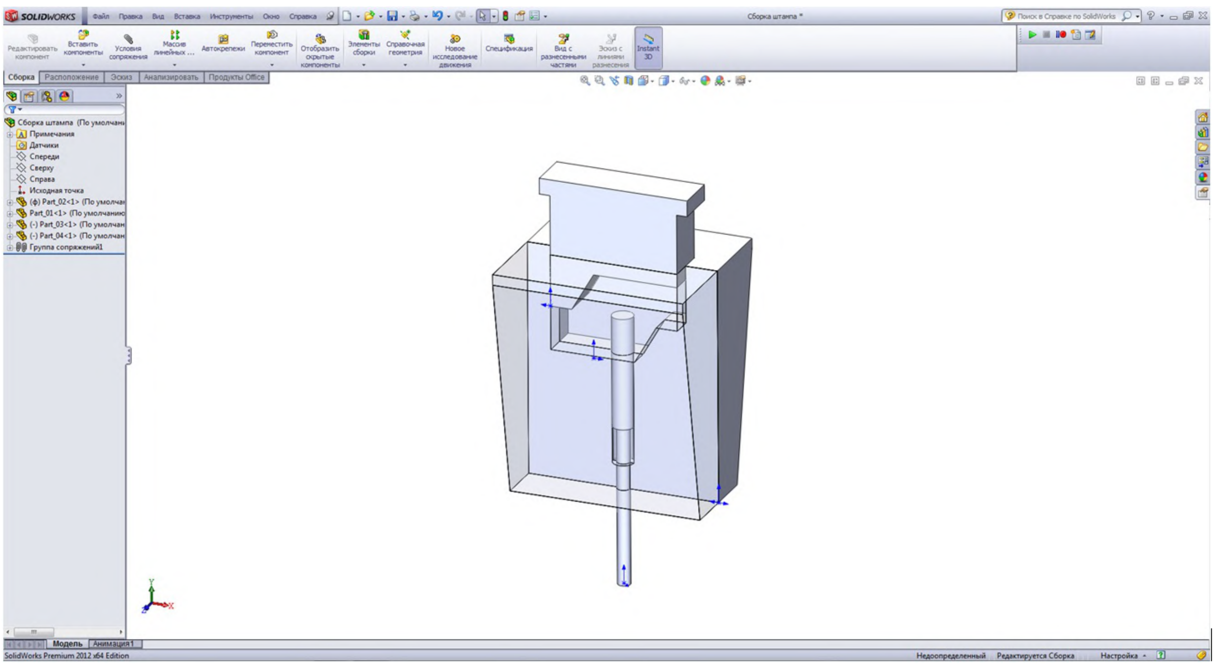

Figure 7. The 3D model of the equipment is generated in SolidWorks CAD.

necessary to select a file with the results of calculations in .odb format. In the Objects field, a list of all parts of the model is displayed. A list of all calculation steps is displayed in the Steps field (figure 5). The Parameters field displays a list of parameters whose values can be imported. The researcher in each field chooses the values he needs for further analysis of the technological process. Next, you need to press one of the buttons in the lower part of the module.

As a result of the simulation cycle, one of the technological process options is selected. The interface of the "Geometry" module (figure 6) displays the parametric model of the selected technological process and allows you to make changes to the dimensions. Clicking on the "Transfer to CAD" button leads to the transfer of a 3D geometric model to the SolidWorks CAD system (figure 7). Interaction with SolidWorks CAD is implemented using the SolidWorks API.

5. Conclusions

The analysis of the state of research in the field of the use of automated design systems made it possible to formulate the problems of creating integrated AMS in the field of processing materials by pressure and to develop typical stages of modeling technological processes for SPD processes. It has been established that a number of problems are solved based on the development of parametric models of billets and die sets used in SPD processes. These models are the basis for choosing a deformation scheme and integrating CAD/CAE systems into a single CAD system. The use of parametric models for the construction of geometry in CAD systems and calculation models for CAE systems increases the degree of automation of the design of technology for processing materials under pressure.

The structure of the object-oriented iAMS core has been developed, which provides an increase in the functionality of iAMS by combining a number of external modules for modeling a number of technological schemes, and adequate modeling of the behavior of materials in deformation processes.

A two-stage approach to modeling the multi-stage SPD process is proposed. In the first stage, preliminary calculations are performed to determine the comparative efficiency of the studied deformation schemes, for which mathematical models and a method of calculating the change in the cross-sectional area of billets in dies of different shapes are developed.

Object-oriented software in the C# programming language was developed to analyze the influence of different initial shapes of the billets and the die sets on the degree of change in the cross-section of the billet during SPD according to the reverse shear scheme of RS-60 and RS-180. Analysis of the influence of the cross-section geometry of the punch showed that increasing the angle of inclination of the punch surface intensifies the process of deformation of the billets. The analysis also showed that the influence of the angle of inclination of the deforming surfaces of the die most significantly affects the degree of change in the shape of the cross-section of the billets. The degree of this influence is most pronounced for billets with a cross-section in the form of a parallelogram.

In the second stage, an analysis is carried out using the CAE system of the stress-strain state of the billet and the stability of the behavior of the billet during deformation, since an increase in the angle of inclination of the deforming surfaces of the punch can lead to the turning of the billet or an unstable passage of the deformation process.

In the course of further improvement of the software, it is planned to develop a common format for storing the description of the SPD process in XML format.

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Design of rapid-hardening cementitious repair mixtures for increasing the sustainability of concrete structures

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Abstract. The article presents designe of rapid-hardening, non-shrinking cementitious mixtureses, which allows solving the problem of rehabilitation of concrete structures and has a positive effect of environmental sustainability. To ensure the maximum dense packing of the cement mixture, the granulometric composition of the sand was optimized. Mathematical models of physical and technical indicators of repair mixtures based on Portland limestone cement and optimized sand composition were obtained, which quantitatively characterize the action of high-alumina fly ash, sodium hydroaluminate, polycarboxylate ethers with increased rapid hardening, early strength, adhesive strength and reduction of shrinkage deformations. A combination of Portland limestone cement, fly ash, polycarboxylate ethers and alkaline activator ensures the intensification of early structure formation due to the formation of hydrocarboaluminates and alkaline hydroaluminosilicates; larger fractions of limestone particles and fly ash act as a microfiller, which in the complex contributes to increasing the early strength and stability of the cementitious matrix.

1. Introduction

Currently, sustainability is an important issue worldwide [1], particular in the construction [2]. The production of cement and concrete is responsible for the production of 7% of the total CO_2 emissions in the world [3], since concrete is the second most used commodity in the world [4]. That means that it is used a lot and that use costs money, pollution, and energy. Concrete is an excellent construction material (low cost, shapable, fire resistance, low-tech but robust production from widely used raw materials). When done right, concrete is the most environmentally friendly material on the planet. In this case, it is possible to build durable concrete structures that have a service life of 100+ years [5].

At the same time, environmental degradation in the world leads to ecological and other problems. That is why it is necessary to use environmentally friendly materials for the rehabilitation of buildings [6]. In Europe, in recent years, the budget for maintenance and repair has been about half of the cost of construction. In Ukraine, the number of destroyed buildings has increased dramatically as a result of the war. One of the cardinal and most economical ways of rebuilding houses is rehabilitation instead of reconstruction of damaged concrete structures [7].

The sustainability of concrete structures is crucial, especially due to the use of concrete as the main construction material. The problem of concrete repair and rehabilitation is becoming increasingly important due to its positive impact in terms of socio-economic benefits and environmental sustainability. The built environment is responsible for about 40% of global emissions over the entire life cycle of a project [8].

In accordance with the directions of sustainable development, concrete structures must meet technical and functional requirements throughout their life cycle [9]. At the same time, under the influence of external loads and environmental influences, reinforced concrete structures are prone to damage. Cracks in reinforced concrete reduce the durability of structures and lead to their unsuitability during operation. Therefore, the problem of repairing building structures using various types of construction mixtures is currently acute. At the same time, it is necessary to ensure the speed of curing of repair mortars, as well as the durability and reliability of buildings [10, 11].

Special repair mixes are used to repair the original surface quality of concrete structures. The use of such materials in concrete surface repair eliminates the need to completely replace the damaged area. At the same time, a balance should be maintained between the manufacturability of applying thixotropic repair mixtures, the final strength, the rate of strength gain, and the durability of the repaired structure [12]. Therefore, there is a need to find formulation solutions to regulate the properties of repair mixtures based on Portland cement systems, in particular, the rate of hardening and durability. Currently, cement, polymer and polymer-modified mortars are used to repair concrete structures [13].

Cement-based mixtures are widely used materials for the repair of reinforced concrete structures [14]. These materials are compatible with the concrete substrate in terms of their material composition, have adhesion to the substrate and ease of repair work [15]. In addition, in order to improve their durability, active mineral additives, fly ash [16], blast furnace slag [17], and zeolite [18] are often used in the mixtures [19, 20].

At the same time, cement repair mortars usually have problems with high shrinkage [21, 22]. Therefore, a promising direction is to modify cement-based repair materials using new generation superplasticisers [23]. According to Liu et al. [24], During curing, such cements can compensate for the shrinkage of concrete and maintain the required stress state for a long period of operation. In addition, repair mixtures should be characterised by high frost resistance and water resistance, and the main requirement for high-quality repairs and an important condition for the long-term operation of repaired concrete is to ensure the compatibility of repair materials with the damaged base both in the hardened state and during curing [25]. During curing, such cements can compensate for the shrinkage of concrete and maintain the required stress state for a long period of operation. In addition, repair mixtures should be characterised by high frost resistance and water resistance, and the main requirement for high-quality repairs and an important condition for the long-term operation of repaired concrete is to ensure the compatibility of repair materials with the damaged base both in the hardened state and during curing [26].

When using repair mortars, it is often necessary to accelerate their curing kinetics in the early period of hydration. Since rapid setting of cement mixtures is required during repairs, curing accelerators are introduced into their composition [27, 28]. The accelerators used are alkaline accelerators based on alkaline aluminates or alkaline silicates, alkali-free accelerators developed on the basis of mixtures of aluminium sulfate and hydroxide [29, 30].

Alkali-activated materials are environmentally friendly repair materials and they have good potential for use in concrete repair [28,31]. However, the problem with their use is high shrinkage and cracking [32]. The joint effect of dihydrate gypsum and alkali metal salts additives can have a significant impact on the early structure formation of grouting systems [33]. At the same time, carbonates and silicates of alkali metals lead to accelerated cement dough hardening and loss of plastic properties of the system due to their interaction with gypsum dihydrate [34]. Therefore, the expediency of using neutral salts, such as Na_2SO_4, $Na_2S_2O_3$, $Na[Al(OH)_4]$, etc. [35, 36].

Currently, sodium aluminate $Na[Al(OH)_4]$ is an effective alkaline additive that increases the water resistance of concrete and mortars [37]. This alkaline accelerator significantly reduces the shrinkage of mortar and concrete and increases their crack resistance [38]. The principle of operation of such an additive in mixtures is to accelerate the hydration of cement with the formation of submicrocrystalline hydrated phases, which provides high strength [39, 40]. Aluminium accelerator increases the concentration of $Na[Al(OH)_4]$ – in the cement batter. This means that a significant portion of the aluminium coming from the accelerator must be absorbed in the earliest hydration period. Thus, as a result of the reaction with the $Na[Al(OH)_4]$ accelerator, rapid formation of C-A-H phases occurs in the cement batter, which leads to a higher water demand in the cement [41].

Krivenko et al. [42] showed that the introduction of PCE polycarboxylate superplasticizers slows down the setting time, improves the consistency, and reduces the rapid development of the strength of cementing system. Alkali-aluminate nanocomposite with polycarboxylate esters of the C-A-N-H-PCE type belongs to the class of engineering materials. The structure of the nanocomposite consists of layered double hydroxides (CaAl LDH) and organic additives synthesised by sol-gel technology, which makes it possible to produce non-shrinking, fast-hardening cements.

On the other hand, purposeful formation of their mesostructure is important for repair mixtures [43]. Improper design of repair mixtures is a frequent cause of damage and destruction of restored surfaces. Improved operational properties (shrinkage deformations, crack resistance, bond strength with the base, waterproofing, etc.) can be achieved by properly selected granulometric composition of sand, as well as by the introduction of mineral additives [44, 45]. Fly ash is widely used as an additional cementitious material (SCM) for concretes and mortars [46]. The main component of fly ash is a vitreous aluminosilicate phase in the form of spherical particles up to 150 µm in size, which allows increasing the workability of concrete and mortar mixtures [47]. The introduction of fly ash allows reducing heat generation and shrinkage deformations of concrete, providing economic and environmental advantages [48, 49]. The above data show that in order to ensure the rapid restoration and repair of elements of buildings and structures, there is an urgent need to search for prescription solutions for regulating the properties of cement mixtures.

The aim of this article is to design the compositions of rapid-hardening, non-shrinking cementitious mixtures for increasing the sustainablity of concrete structures, to study the processes of their structure formation and the determination of physical and mechanical properties.

2. Raw materials and testing techniques

The samples under study were Portland cements CEM II/A-LL 42.5 R (SSA = 3900 cm^2/g) produced by JSC Ivano-Frankivskcement (Ukraine). Portland cement clinker was characterized by the following mineral composition (mass.%): C_3S – 62.5, C_2S – 13.8, C_3A – 6.7, C_4AF – 12.3; content of alkaline oxides in the clinker (mass.%) was: K_2O – 1.2 and Na_2O – 0.14.

The active mineral aluminum-containing additive fly ash (FA) from Burshtyn TPP was used for research. The specific surface area of the fly ash is $SSA = 4200\,\mathrm{cm}^2/\mathrm{g}$. For fly ash, the content of the fraction up to $1\,\mu$m is 2.21%, the maximum surface activity in the bimodal distribution reaches $K_{\rm isa} = 3.81\mu\mathrm{m}^{-1}$vol.% and $K_{\rm isa} = 2.42\,\mu\mathrm{m}^{-1}$vol.% and is assigned to particles of $0.23\,\mu$m and $3.85\,\mu$m in size.

The alkaline curing activator sodium tetrahydroxoaluminate $Na[Al(OH)_4]$ was used. The mass fraction of sodium aluminate in the additive is 40 mass. %. The pH of the sodium aluminate solution is 13.0 – 13.3. As a superplasticizer based on polycarboxylate ethers (PCE) was used. The complex modifier $Na[Al(OH)_4]$-PCE was used in the development of a rapid-hardening non-shrinkage cementitious repair mixtures. Determination of the effectiveness of additives that accelerate curing, increase the strength of cement mixtures of the basic composition ΔR was carried out in accordance with DSTU B V.2.7-69.

Fine aggregate sands with a fineness modulus of $FM_{1.25}$ (fine sand of the Davydiv deposit, Ukraine) and $FM_{2.76}$ (coarse monofractional sand) were used to design the composition of cement mixtures. The void content of these sands is 46.5% and 47.5%, respectively, and the content of clay and dust particles does not exceed 1.5 mass. %, in particular, for fine sand. Optimization of sands was carried out to obtain a mixture of fine aggregate in the ratio $FM_{2.76} : FM_{1.25} = 100 : 0$; 75 : 25; 50 : 50; 25 : 75; 0 : 100. Fly ash was used to study the characteristics of the optimized composition of the sand mixture.

Tests of granulometric composition, fineness modulus, bulk density, and void content of sands were carried out in accordance with DSTU B V.2.7-232:2010. The workability of the fresh mixtures was measured on a flow table according to EN 1015-3. The compressive and flexural strengths of the cement mixtures were determined on prism specimens measuring $40 \times 40 \times 160$ mm. The strength of the mixtures was measured after 14 h, 24 h, 2 and 28 days under different curing conditions. The shrinkage-expansion deformations of the mixtures were studied on $20 \times 20 \times 160$ mm beam specimens stored in water for 7 days of curing, after which the specimens were cured in air-dry conditions. The adhesion strength of the repair mixture to the substrate was determined by the method of tearing off a metal tear-off with subsequent assessment of damage. The chemical composition of Portland cement clinker was determined using the X-ray spectrometer ARL 9800 XP. The particle size distribution of the fly ash was obtained using a Mastersizer 3000 analyzer by laser diffraction. The phase composition of the initial substances and interaction products was studied using X-ray diffractometry.

3. Results and discussion

To ensure the densest possible packing of the cementitious mixtures, the grain size distribution of sand of different particle size distribution was optimized. It was found that the bulk density of coarse sand with $FM_{2.76}$ and very fine sand $FM_{1.25}$ is 1463 kg/m^3, and when compacted, it reaches 1673 and 1600 kg/m^3, respectively. For a mixture of $FM_{2.76} : FM_{1.25}$ sands in the ratio of 75:25, 50:50, 25:75, the bulk density increases and reaches 1533 kg/m^3, 1522 kg/m^3, 1479 kg/m^3, and when compacted, it increases to 1690 kg/m^3, 1673 kg/m^3, 1655 kg/m^3 compared to sands with $FM_{2.76} : FM_{1.25} = 100 : 0$; 0 : 100. When mixing 25 mass. % coarse sand ($FM_{2.76}$) and 75 mass. % of fine sand ($FM_{1.25}$), the modulus of the mixture increases from 1.25 to 1.57, and the void decreases by 10.7%. For a mixture of sands $FM_{2.76} : FM_{1.25} = 50 : 50$, the fineness modulus increases from 1.25 to 1.85, the void decreases from 46.8% to 42.5%, and the bulk density increases from 1410 kg/m^3 to 1522 kg/m^3. With a decrease in the content of fine sand in the mixture to 25% ($FM_{2.76} : FM_{1.25} = 75 : 25$), the fineness modulus increases to 1.87 ($FM_{1.87}$), and the lowest void in the bulk and compacted states is characteristic, which is 42.2% and 36.2%.

The effect of fly ash on the characteristics of the optimized composition of a mixture of sands with $FM_{1.87}$ was investigated. The ratio of sand with $FM_{1.87}$ and fly ash was changed: $FM_{1.87} : FA = 100 : 0$; 75 : 25; 50 : 50; 25 : 75; 0 : 100. It was found that increasing the amount of fly ash in the mixture to 75 mass. % leads to a decrease in the bulk density to 1150 kg/m^3 and an increase in the void content to 52.1%. At the same time, the composition with a ratio of $FM_{1.87} : FA = 75 : 25$ is characterized by the highest bulk density of 1683 kg/m^3 and the lowest void content of 35.3%.

Based on the obtained results, the design of effective compositions of rapid-hardening non-shrinkage mixtures was carried out using two-factor mathematical planning of the experiment. The optimized sand composition with $FM_{1.87}$ was used in the experiment. The composition of the repair mixture without additives (Cement : Sand = 1 : 2) was taken as a reference. Fly ash ($0-20.0$ mass.% (X_1)) and a complex modifier - Na[Al(OH)$_4$]-PCE($0-5.0$ mass.% (X_2)) were used as variable factors. When changing the formulation levels of the selected factors, the mobility of the cement mixture was stabilized at the Flow $170-180$ mm.

Based on the results of the calculations, isoparametric diagrams of changes in the hardening time, compressive and flexural strength after 14 h; in compression after 28 days under normal conditions and at $T=-5...+5\,°C$ of curing were constructed (figure 1, a-f). For the mixture without additives ($W/C=0.38$), the initial and final settings times are 240 and 285 min, respectively.

The introduction of 2.5 mass.% Na[Al(OH)$_4$]-PCE (X_2) leads to an increase in the water requirement of the repair mixture from 0.38 to 0.40. In this case, the early strength after 14 hour of curing increases from 1.8 to $2.9-3.0$ MPa, after 1 and 28 days it is 18.9 MPa and 63.7 MPa; after 2 days the strength is 34.2 MPa. An increase in $Na[Al(OH)]_4$-PCE to 5.0 mass.% leads to a reduction in the curing time to 90 min. At the same time, the strength decreases by 12 % at the age of the 1 day and by 5.0% after 28 days of curing under normal conditions. The introduction of 10 mass.% fly ash into the mixture, which determines the factor (X_1), offsets the negative impact due to the plasticizing effect, which, depending on the content, leads to a decrease in W/C from 0.43 to 0.41, with the initial settings time of 235 min. Thus, the introduction of 10.0 mass.% fly ash and 5.0 mass.% Na[Al(OH)$_4$]-PCE allows obtaining accelerated settings times - 70 min (initial) and 140 min (final), and high early flexural and compressive strengths - 3.7 MPa and 10.0 MPa, respectively. The highest standard strength (70 MPa) is characterized by the mixture with additives of 2.5 mass.% Na[Al(OH)$_4$]-PCE and 10.0 mass.% fly ash. It is shown that an increase in the fly ash content to 20.0 mass.% leads to a slower hardening time and a decrease in strength. Reducing the fly ash content to $5.0-7.0$ mass.% in the mixture with the simultaneous introduction of 5.0 mass.% Na[Al(OH)$_4$]-PCE will accelerate the hardening time to $30-40$ min and obtain the required strength characteristics.

It was found that for mixtures modified with 2.5 mass.% Na[Al(OH)$_4$]-PCE after 28 days of curing under variable curing conditions ($T=-5...+5\,°C$), the compressive strength is 56.0 MPa. Under conditions at low positive and negative temperatures, the highest strength (57.0 MPa) is characterized by a mixture containing 5.0 mass.% alkaline modifier $Na[Al(OH)_4]$-PCE.

Analysis of the experimental data of mathematical modelling in a given interval of changes in the composition ratio shows that the introduction of an optimal amount of $2.5-5.0$ mass.% Na[Al(OH)$_4$]-PCE and 10.0 mass.% fly ash into the composition of the modified repair mixture and the optimal composition of sand ($FM_{2.76}:FM_{1.25}=75:25$) provides a compressive strength of $66.0-70.9$ MPa after 28 days. It was established that the high technical effect of the repair mixture is achieved after 14 hours ($\Delta R_{c14}=64.0\%$). Thus, the optimal composition of the non-shrinkage repair mixture (2.5 mass.% Na[Al(OH)$_4$]-PCE and 10.0 mass.% fly ash) can be classified as a rapid hardening mixture ($R_{c1}/R_{c28}=31.0\%$; $R_{c2}/R_{c28}=63.0\%$, $R_{c28}=70.9$ MPa).

Studies of the deformations of cement mixtures have shown that during 7 days of curing in water, insignificant expansion deformations are observed for all compositions, varying from 0.10% (0.06 mm/m) to 0.15% (0.25 mm/m). After 28 and 56 days of curing in air-dry conditions, the cement mixture without additives has the highest shrinkage strains (0.78 and 0.81 mm/m). For the developed rapid hardening cement mixture (2.5 mass. $Na[Al(OH)_4]$-PCE and 10.0 mass.% fly ash), the shrinkage deformation is 0.08 mm/m. The adhesion strength to the concrete base after 28 days is 3.2 MPa.

The method of X-ray phase analysis was used to study the hydration characteristics of cement paste modified with the combined alkaline additive Na[Al(OH)$_4$]-PCE after 1 day of hardening. As can be seen from figure 2, the phases of portlandite ($d/n=0.263; 0.492$ nm) and ettringite ($d/n=0.973; 0.560$ nm) are fixed for cement paste without additives after 1 day of hardening. At the addition of 2.5% Fly ash- Na[Al(OH)$_4$]-PCE in 2.7 time decrease of the portlandite line

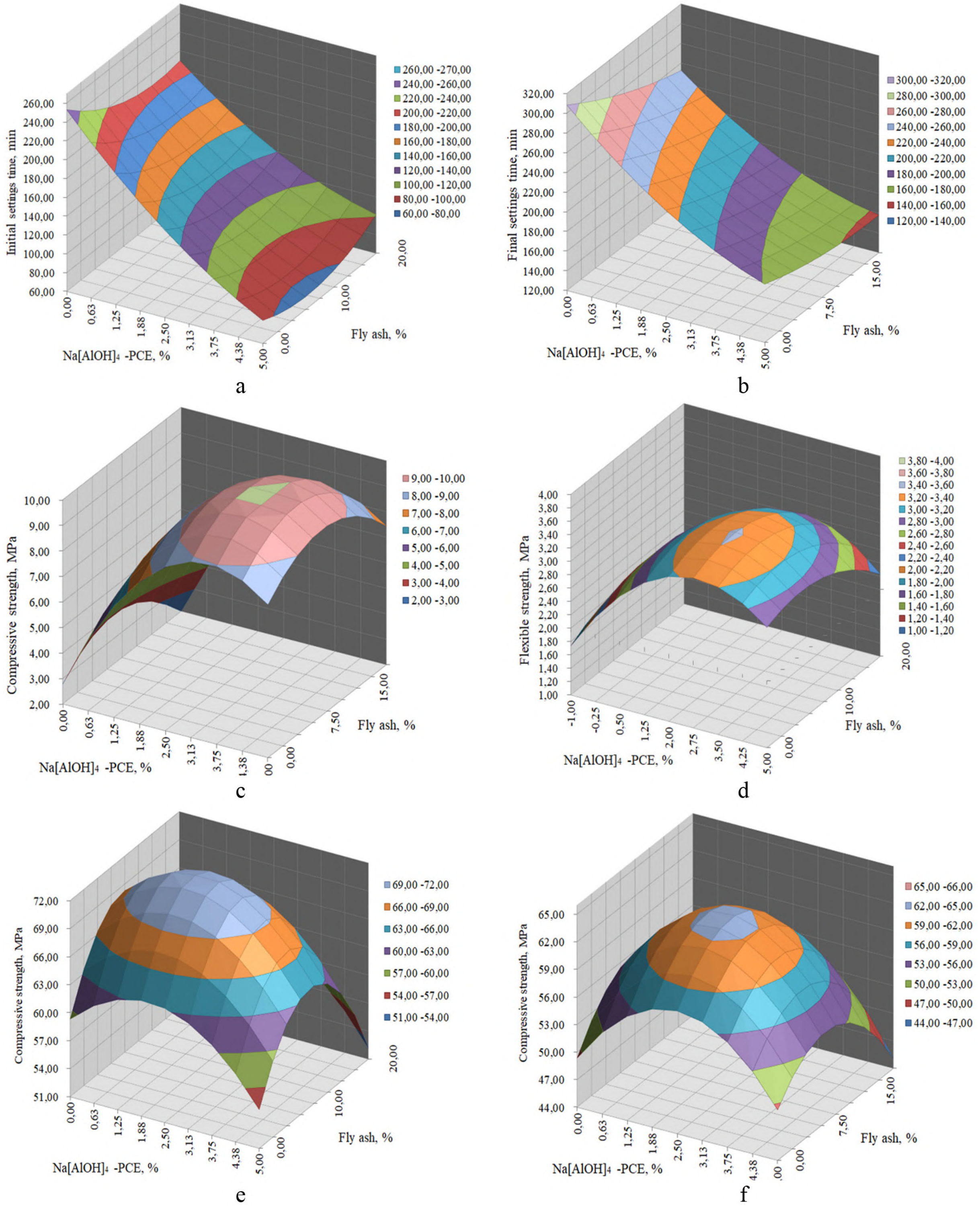


Figure 1. Isoparametric diagrams of changes in the initial (a) and final (b) hardening times, compressive and flexural strengths after 14 hours (c, d), compressive strength after 28 days under normal conditions (e) and at $T = -5 ... +5\,^{\circ}\mathrm{C}$ (f) hardening.

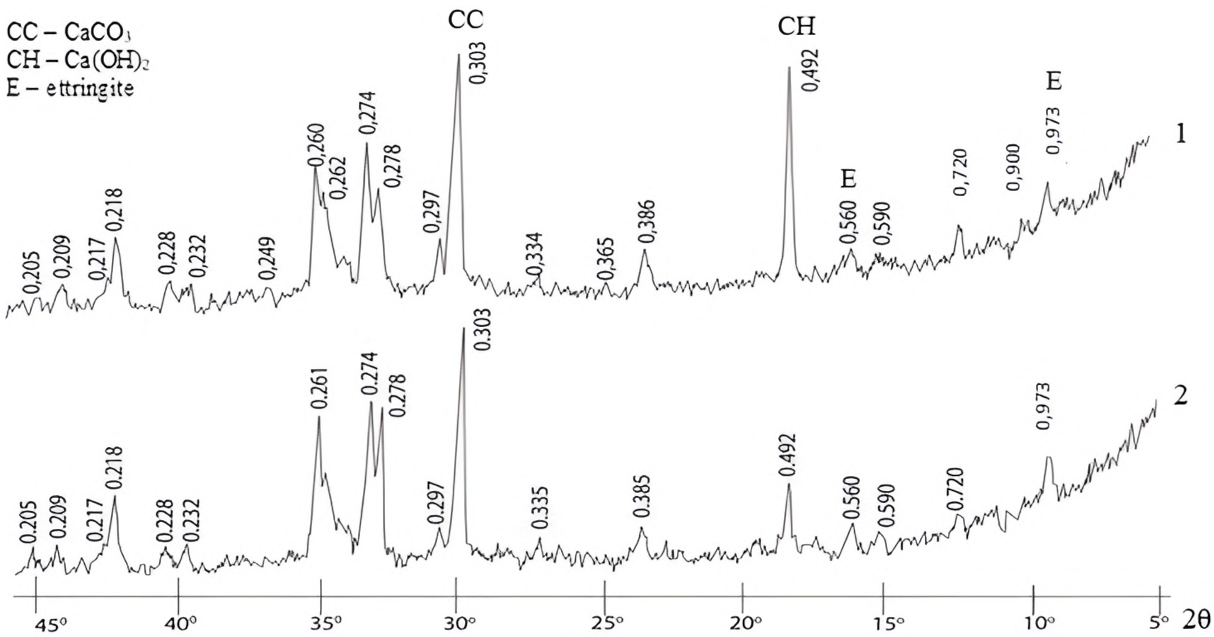
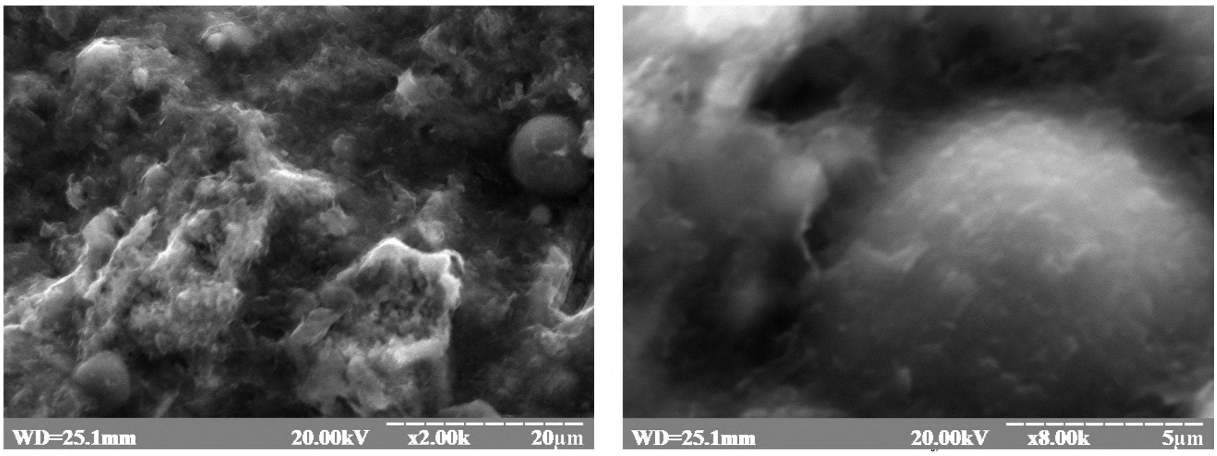


Figure 2. Diffractograms of paste at the age of 1 day: 1 – without additives; 2 – FA-Na[Al(OH)$_4$]-PCE.

was observed, this indicating an intensive pozzolanic reaction in the modified cement paste.

It was shown by electron microscopy that the cement paste based on CEM II/A-LL with fly ash modified with the combined alkaline additive Na[Al(OH)$_4$]-PCE after 1 day of hardening is characterised by a dense microstructure. Fly ash particles of 6-8 µm in size fill and colmatise the micropore of the modified cement paste (figure 3, a).

The fly ash particles are covered with a densely packed fine crystals, which indicates the passage of the pozzolanic reaction with the formation of low-basic C-S-H phases (figure 3, b). The acceleration of the early structure formation processes is provided by the alkaline activator Na[Al(OH)$_4$] with the formation of zeolite-like hydroaluminosilicates N-C-A-S-H.



a b

Figure 3. Microstructure of modified cement paste with FA-Na[Al(OH)$_4$]-PCE.

When PCE is added to the cement paste, a finely dispersed microstructure is formed due to the phenomenon of adsorption modification of hydrate neoplasms. The complex combination of CEM II/A-LL with the addition of limestone, fly ash, and alkaline activator $Na[Al(OH)_4]$ provides intensification of early structure formation processes through the formation of hydrocarboaluminates and alkaline zeolite-like hydroaluminosilicates; larger particles of limestone and fly ash are used as microfillers, which in combination increase the strength and durability of cementitious matrix.

4. Conclusions

1. The formation of a continuous mesostructure of cement mixtures is achieved by the correct design of the grain composition of fine aggregates, the optimal ratio between their components "sand – fly ash". Replacing part of the sand with fly ash increases the density of the cementing matrix in concrete, which allows to reduce the impact on the environment.
2. The analysis of experimental data from mathematical modeling shows that the introduction of $2.5 - 5.0$ mass.% $Na[Al(OH)_4]$-PCE and 10.0 mass.% fly ash into the modified repair mixture based on the optimized sand composition ($FM_{2.76} : FM_{1.25} = 75 : 25$) provides an accelerated setting time of 60-70 min, compressive strength after 14 h - 8-10 MPa, and 28 days - 66.0-70.9 MPa. The high technical effect is achieved after 14 hours ($\Delta R_{c14h} = 64.0\%$).
3. It was established that in the presence of polycarboxylate ester PCE additives, due to the phenomenon of adsorption modification, the size of the formed crystals decreases, which leads to a significant increase in the density and impermeability of the cement paste; due to the phenomenon of "self-reinforcement" by formation of finely dispersed low-base C-S-H phases and zeolite-like N-C-A-S-H hydroalumino silicates the strength and durability of the repair mixture increase.
4. Complex implementation of the effects of physical optimization and alkaline activation ensures the production of effective rapid-hardening, non-shrinking cementitious mixtures for the repair of concrete structures in accordance with the requirements of sustainability.

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Electrospark method of obtaining metal nanoparticles for the creation of antifungal drugs (fungicides)

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Electrospark method of obtaining metal nanoparticles for the creation of antifungal drugs (fungicides)

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Abstract. The research is based on the processes of studying electrospark underwater synthesis of conductive metals in a reaction chamber with low conductivity for the production of metal nanoparticles. Experiment had been carried out using confirmation of silver and copper nanoparticles by electron microscopy. The use of nanoforms of metals, in particular nanosuspensions, is considered as an alternative to acutely toxic chemical preparations in crop production for the protection of field crops. Strains of microorganisms – causative agents of diseases of grain crops were used as objects of research. The ultrafine metal phase of metal nanoparticles (particulate nature of matter – PNM) is considered as an alternative to existing agrochemicals based on metal salts. The obtained colloidal solutions of metals have fungicidal properties and can be used to create plant protection products.

1. Introduction

The issue of the biological impact of nanomaterials remains key in fundamental studies of the interaction between nanoparticles and the biological environment. A new direction of research of solutions based on metal nanoparticles, which exhibit a wide spectrum of biocidal activity, enables their usage as disinfectants, antibacterials, and antifungals. Resulting solutions are not toxic to humans and the environment. Usage of nanoparticles in solutions had been determined very effective not only due to their relative size, but also because of the specific method for obtaining nanoscale objects. Particular attention should be paid to the study of the effect of metal nanoparticles on the causative agents of many human infections and diseases and plant pathogens. These include staphylococci and phytopathogens that cause significant crop losses of *Penicillium sp.* and *Alternaria alternate*. Metals with antifungal action – copper and zinc – are considered as fungicides [1]. Usually, either metal salts (sulfates) or various nanoforms of metal particles and their oxides are used [2–5]. The largest number of studies is devoted to the study of the bactericidal activity of silver. In addition, bactericidal activity was found in gold and some other elements, including carbon nanoforms [6–9].

2. Materials and methods

The use of discharge pulse power generators (DPPG) for the synthesis of metal nanoparticles makes it possible to obtain low-temperature plasma in the discharge channel in a short period of time, which ensures effective erosion of the anode material. A unique feature of the volumetric electrospark dispersion method is the presence of a conductive layer of granules located between the main electrodes. The process takes place in a reaction chamber filled with a weakly conductive liquid, namely: deionized water. Voltage supply to the main electrodes are caused by the passage of current through a chain of freely stacked granules in the stochastic switching mode. The use of low voltages (up to 150 V) and small interelectrode gaps makes it possible to provide modes when up to 85% of all accumulated energy on the capacitor is used for local heating of the surface of the contacting granules. A layer of conductive metal granules with a maximum diameter of 5-10 mm is used to ensure the performance of spark erosion dispersion instead of a single contact gap. With the help of a thyristor generator with capacitive energy storage, discharge pulses were obtained, the amplitude of the voltage of which was regulated in the range of 40 – 150 V, and the current – from 30 to 500 A (figure 1).

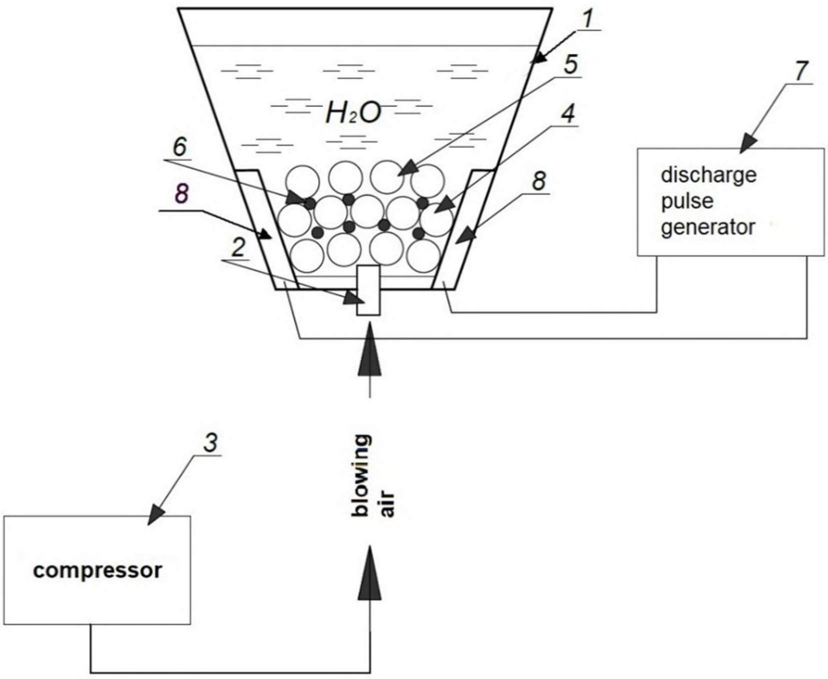

Figure 1. Technological complex for obtaining metal nanoparticles – discharge chamber (1); air sprayer (2); compressor (3); metal granules (4, 5); discharge (plasma) channel (6); discharge pulse generator (7); electrodes- anode and cathode (8).

The system of metal granules and plasma channels immersed in a dielectric liquid and ohmic contacts between them is a complex electrical load. It has a significant nonlinear character and significant parametric dependencies on a number of technological factors: the frequency of discharge pulses, the flow rate and the temperature of the working fluid, etc. In addition, the physical nature of the occurrence of spark discharges in the layer of conductive granules determines the stochastic migration of plasma channels along their surface and switching current flow paths to adjacent pairs of granules. As a result, the instantaneous values of the equivalent electrical resistance of such a medium vary widely: from 0.05 to 100 *ohms*. The frequency of discharge pulses is regulated in the range of 100 – 200 *Hz* and the inductance of the discharge

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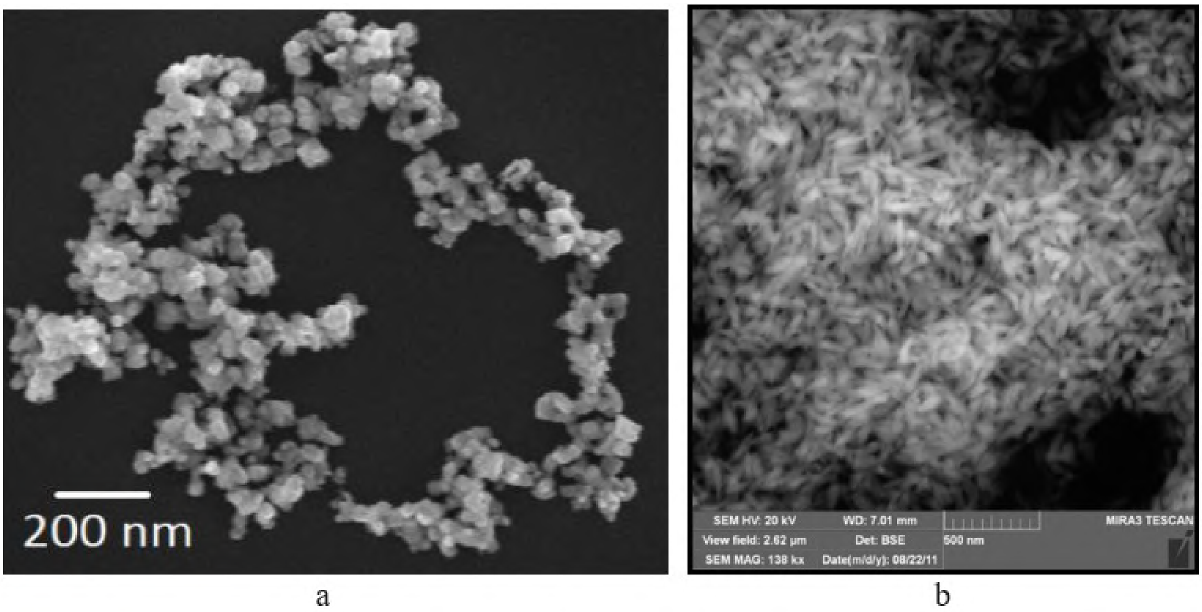

Figure 2. Electron microscopy (SEM) of nanoparticles – Ag (a), Cu (b).

circuit L does not exceed 1 μH.

3. Results and discussion

The result of electrospark treatment of granules is the formation of a nano-sized fraction of the corresponding metals, which are in colloidal form and of sufficient concentration (100-1000 *ppm*) for microbiological research.

Micromycetes of *Penicillium sp.* and *Alternaria alternate* were used as microbiological objects of research. They were obtained from the collection of microbial cultures of the Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine. Nanosuspension of silver and copper with average particle sizes from 20 to 50 *nm* were used as fungicides. For the research we have studied the effect of metal compound solutions on the survival of microorganisms after 30 minutes of incubation at the optimal temperature. The conducted

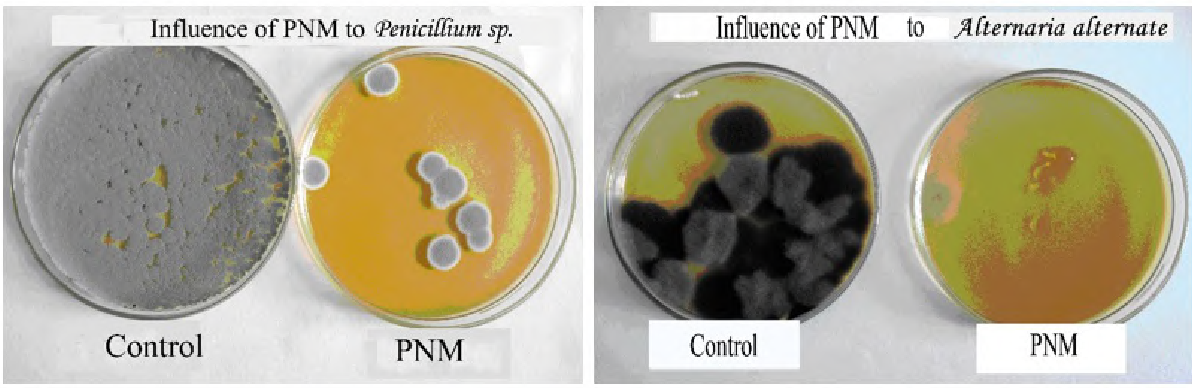

Figure 3. Influence of PNM Ag and Cu on survival microscopic fungi Penicillium sp and Alternaria alternate with.

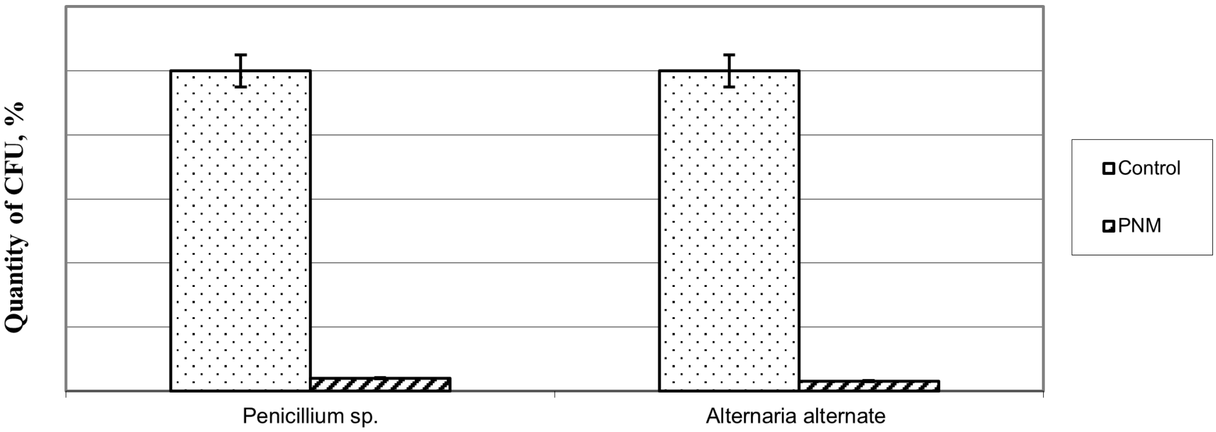

Figure 4. Survival microscopic fungi Botrytis cinerea and Alternaria alternate in action PNM Ag and Cu expressed in percent to control.

test results showed that in the concentration range of 5-50 *ppm*, mixtures of silver and copper compundsolutions have a pronounced fungicidal action on microscopic fungi Penicillium sp. and Alternaria alternate. As a result we found out that the inhibition of germinated conidia of micromycetes was up to 97% in relation to the control. The test results indicate that particulate nature of matter (PNM) solutions prepared based on Ag and Cu at a concentration of 8 *mg/l* are effective fungicidal agents for Penicillium sp. and Alternaria alternate (figure 3 and figure 4).

4. Conclusions

As a result of the study of the bactericidal effect of combined PNM Ag/Cu on microorganisms, pathogens of infectious diseases, it was found that they exhibit a fungicidal effect against the studied strains of microorganisms with a metal in low concentrations, inhibiting the growth of pathogenic microflora by 90-97%. Besides, the study of the effect of PNM data on the micromycetes of *Penicillium sp.* and *Alternaria alternate* indicate that the research solutions can be used as effective fungicidal agents. The use of PNM can solve the problem of using highly toxic chemical fungicides and biocides. The PNM enables solutions to inhibit the growth of pathogenic microorganisms by almost 100%, additionally such solutions are non-toxic to the biological system and have a prolonged effect.

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Chatbot application to support indoor temperature control

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Chatbot application to support indoor temperature control

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Abstract. The article is dedicated to Internet of Things (IoT) technologies that allow connecting various devices and sensors via the Internet. Effective customer interaction with IoT systems requires smart interfaces that take into account the context and human needs. Chatbots are considered that can provide users with convenient support, process data from sensors, and visualize them. An IoT system consisting of sensors, a cloud platform for data storage and processing, a database, and a chatbot interface for user interaction is considered. The automatic indoor temperature control system uses sensors that transmit data to the cloud, where it is processed and stored. Users can interact with the IoT system through a chatbot that understands commands and responds accordingly. The chatbot has been tested, showing that it can autonomously maintain the optimal temperature, changing it according to user commands, and responding to critical situations. The results of the study demonstrated that the use of a chatbot allows you to create a human-centered automated system.

1. Introduction

The Internet of Things (IoT) is one of the most promising areas of information technology development, which involves communication between various devices and sensors via the Internet [1]. IoT systems can collect, process and analyze large amounts of data generated by these devices and use them to improve people's quality of life, business efficiency and environmental safety [2]. However, in order for customers to be able to easily and conveniently interact with IoT systems, intelligent and natural user interfaces are needed. Chatbots are one such interface that uses artificial intelligence (AI) and natural language processing (NLP) to simulate conversations with people or other chatbots using text or voice messages [3]. Chatbots can provide users with comfortable and efficient assistance by answering their questions, providing them with more interesting answers, directly responding to their problems [4]. This article highlights the ability of chatbots to process the substantial amounts of data generated by sensors and IoT systems, and then present this information in a format that is readily comprehensible and actionable for users [5].

The latest research and publications on this topic testify to the high relevance and perspective of chatbots as a user interface for IoT systems. For example, the authors of the paper [6] propose an interdisciplinary scientific program for the future development of chatbots, in which they distinguish six thematic areas:

- users and consequences;
- user experience and design;
- frameworks and platforms;
- chatbots for cooperation;
- democratization of chatbots;
- ethics and privacy.

For each of these areas, they provide a brief overview of the current state of the art, discuss key scientific challenges, and suggest promising directions for future research.

Maginga et al. [7] consider the use of chatbots to solve complex business problems with the help of AI and IoT. They show how chatbots can provide quick and convenient access to large volumes of data generated by IoT devices and analyze this data to improve performance and service quality. They also describe some use cases for chatbots in smart factories, smart homes, and smart healthcare systems.

In the article [8] the authors describe the history, technology and application of chatbots as natural dialogue systems. They consider the development of chatbots in the context of the development of AI, OPM and human-computer interaction. They also analyze the current types of chatbots based on their functionality and architecture. They show how chatbots can be useful in various industries such as education, healthcare, business and entertainment.

The article aims to examine the functionality of chatbots for indoor temperature management utilizing IoT systems. It analyzes the modern programming languages employed in IoT systems. The study involves testing the chatbot's capabilities, enabling users to set the preferred temperature in rooms, monitor the current status of temperature sensors and air conditioning units, and receive alerts about critical situations and the conditions triggering sensor and air conditioning activation.

2. Results

There are various IoT control systems that can be used for a smart home. Some of them offer ready-made solutions with a variety of functions, such as temperature control, lighting, security, etc. Other systems provide a platform for developing your own solutions, which allows for a more flexible approach to solving specific problems.

One of the platforms for IoT development is the Microsoft Azure IoT Suite, which provides tools for collecting, storing, and analyzing data from IoT devices. For a smart home, We can use various devices such as thermostats, motion sensors, security cameras, etc. and connect them to the Azure IoT Hub. This allows you to collect data from these devices and analyze it using Azure Stream Analytics. Another platform is Google Cloud IoT, which provides tools for connecting, managing, and monitoring IoT devices. With the help of Google Cloud IoT, you can connect various IoT devices to the platform and collect data from them for further processing and analysis.

To implement the temperature monitoring function, we use an IoT temperature sensor that reads the data and sends it to the storage system. To understand user commands, we use natural language processing libraries such as NLTK or spacy. They can be used to recognize commands and determine actions to be performed.

After processing the user command, a temperature control algorithm can be applied, which will change the settings of the temperature control system in the house. For example, if a user asks to raise the temperature by 2 degrees, the bot can use this algorithm to raise the temperature in the house. After performing the action, the bot must update the temperature data in the data storage system and notify the user about the result of the action.

When developing an IoT bot to control the temperature in a smart home, we need to analyze existing natural language understanding methods and choose a programming language to develop the bot.

When choosing programming languages for IoT systems, there are several options available, each with their own advantages and disadvantages and areas of application. Table 1 provides an analysis of popular programming languages used in IoT development

Table 1. Analysis of popular programming languages for IoT.

Programming language	Analysis of the application of the programming language for IoT systems
C/C++	Widely used in IoT due to its efficiency, low management level and compatibility with microcontrollers and embedded systems. It provides direct access to hardware, making it suitable for resource-constrained devices. C/C++ are commonly used in IoT platforms, software development, and device drivers [9]
Python	It is a universal and easy-to-learn language known for its accessibility and readability. It offers extensive libraries and frameworks for IoT development, making it popular for rapid prototyping, data analysis, and cloud integration. Although Python may not be as efficient as C/C++, it is often used for higher-level IoT applications, data processing, and scripting [10]
Java	It is commonly used in IoT gateways, server applications, and Android-based IoT devices. Reliability, security functions and scalability of Java make it suitable for large-scale deployment of IoT and corporate solutions [11]
Rust	It is a systems programming language known for its focus on security, performance, and concurrency. It provides memory safety guarantees and strong typing, making it suitable for low-level programming in IoT devices and firmware. Rust is often used in safety-critical applications or where resource efficiency is critical [12]
Lua	It is a lightweight scripting language often used in embedded systems and IoT devices. It is easy to install and provides good performance. Lua is usually used for programming sensor nodes, Internet of Things gateways and creating special software [13]
Swift	Swift is mainly associated with iOS and macOS development, but it is gaining popularity in the IoT due to its security features, expressiveness and compatibility with the Apple HomeKit infrastructure. Swift is suitable for developing IoT applications that integrate into the Apple ecosystem [14]

Ultimately, the choice of programming language for an IoT system depends on factors such as target hardware, resource constraints, scalability requirements, development speed, and available experience. IoT systems typically use a combination of languages at different levels, such as firmware, gateway, cloud services, and web/mobile interfaces. To implement the project, we use Python, which has many libraries and frameworks for developing chatbots and IoT devices.

This study examines an IoT system comprising sensors, a cloud-based platform for data storage and processing, a database, and a chatbot interface to facilitate user interaction (figure 1).

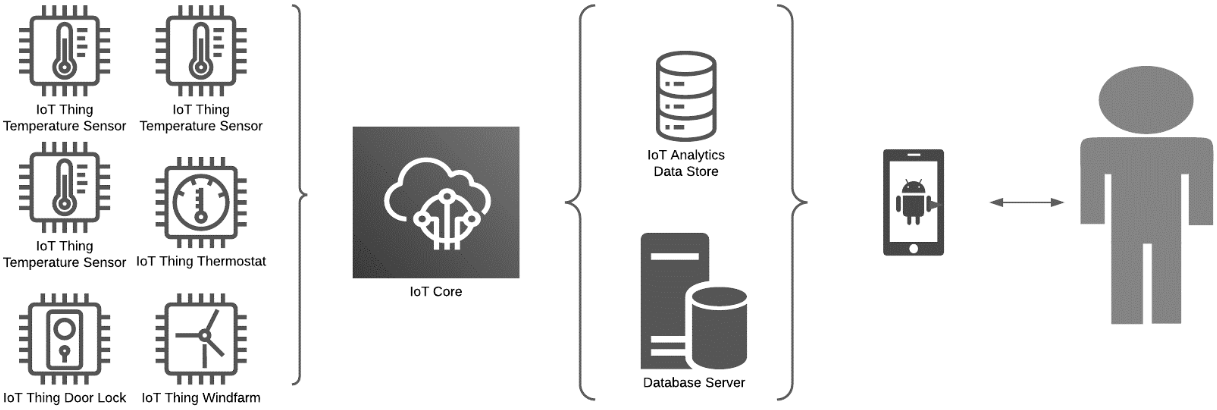

Figure 1. IoT system.

Arduino boards are chosen for IoT devices. The Python development language is used due to its extensive libraries, support for data analysis and ease of integration with IoT devices. PostgreSQL relational database management system is used to store temperature data. This technology provides robust support for SQL queries and can handle large data sets. The psycopg2 library is used to connect to the database from the cloud platform.

The chatbot is written in Python. For the OPM module, the spaCy library is used, which offers advanced functions for tokenization, recognition of named objects, and analysis of syntactic dependencies. Python also provides pre-built models for different languages, which allows for faster application development. spaCy can be used to analyze user queries, extract important objects (eg temperature values, time, location) and understand the context to formulate meaningful answers.

The automated indoor temperature control system operates as follows:

- sensors connected to microcontrollers periodically collect temperature data;
- with the help of special libraries, sensor data are read and stored in the cloud;
- the cloud platform receives temperature data from IoT devices through AWS IoT Core. Python scripts process the input data, perform analysis as needed, and store it in the database;
- a chatbot interface provides users with a conversational interface to interact with an IoT system.

The chatbot understands user commands, retrieves temperature data from the database, and responds accordingly. Users can request current temperature, historical data, set temperature thresholds, or configure other IoT system parameters through the chatbot.

The block diagram in figure 2 illustrates the modules of the presented IoT-based temperature control system.

Let's consider the functions of each block in more detail:

- the chatbot module is an interface between a person and an IoT system. This is software that allows the user to set the desired temperature in each room separately, or to set global parameters for the whole house;

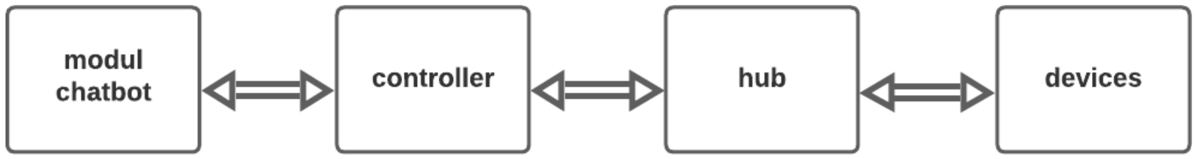

Figure 2. Block structure of IoT-bot modules.

- the controller module analyzes data from the IoT hub and makes decisions about controlling devices to control or change the temperature;
- the IoT hub module collects all data from various sensors and transmits them to the controller module;
- the IoT sensor module includes sensors for measuring temperature, air conditioner operation, open windows, and ventilation grilles. These sensors are connected to the Internet to send data to the IoT hub module.

The system operation algorithm is shown on figure 3.

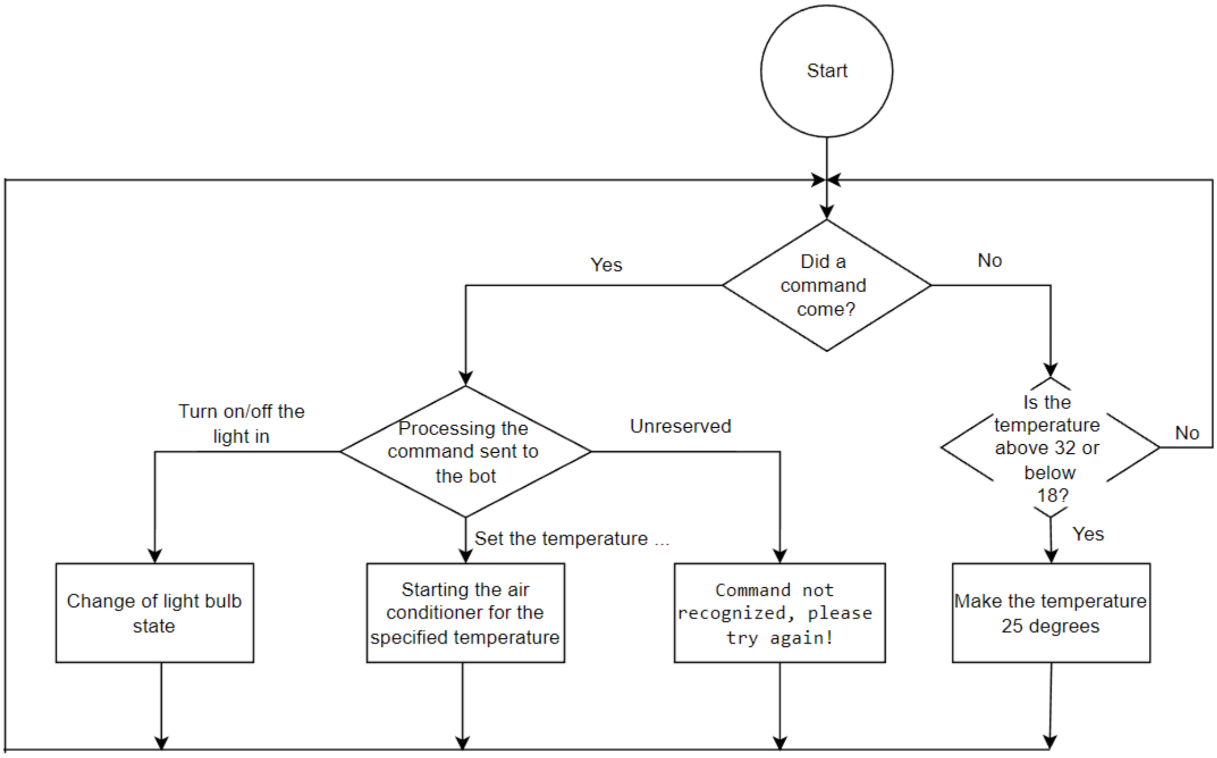

Figure 3. Algorithm of the system.

We can consider the algorithm of chatbot operation with IoT:

- receiving a text command from a user;
- processing a text command using natural language analysis;
- determine the action to be performed based on the processing of a text command;
- interaction with the storage system to obtain information about the temperature in the house;

- application of the temperature control algorithm to change the settings of the thermoregulation system in the house;
- update the temperature data in the storage system;
- sending a response to the user with the results of the action performed.

The chatbot was evaluated in a real-world scenario, tested within a hangar facility spanning 800 square meters. This environment was equipped with a variety of IoT-connected devices, including temperature sensors, air conditioning units, window and door sensors to detect opening/closing, as well as a ventilation system (figure 4). During the testing, the chatbot demonstrated its ability to autonomously maintain the temperature within the hangar, utilizing the air conditioning system to ensure the temperature did not exceed 32 degrees Celsius. The chatbot interface allowed users to interact with the system through text commands, enabling them to adjust the target temperature as desired (figure 5).Crucially, the system incorporates control mechanisms to monitor the status of windows and doors, as well as the ventilation system. Temperature readings were recorded at half-hourly intervals, providing the chatbot with the necessary data to intelligently regulate the environment.The autonomous nature of the chatbot's operation allowed it to proactively manage the temperature without constant human supervision. However, the system was also designed to provide users with a seamless interface to directly manipulate temperature settings, overriding the autonomous control if necessary. This balance of autonomous operation and user interaction represents a key strength of the chatbot-driven IoT solution.Through this real-world evaluation, the chatbot's capabilities were thoroughly tested, demonstrating its ability to effectively maintain optimal environmental conditions within the large hangar space, while also offering intuitive user control capabilities to accommodate specific user preferences and needs.

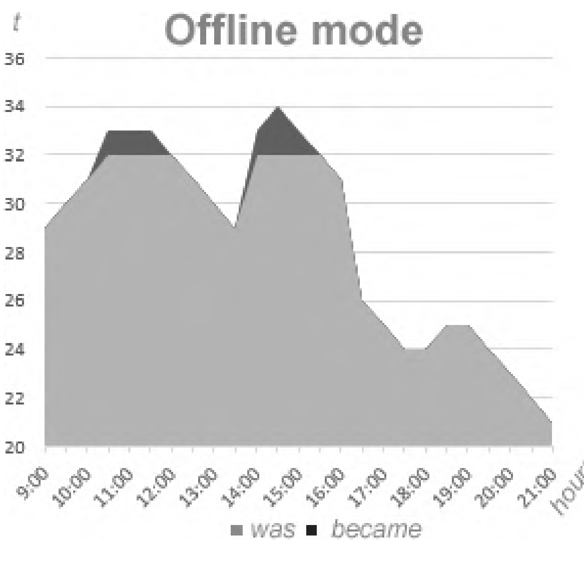

Figure 4. Chatbot operation in offline modes.

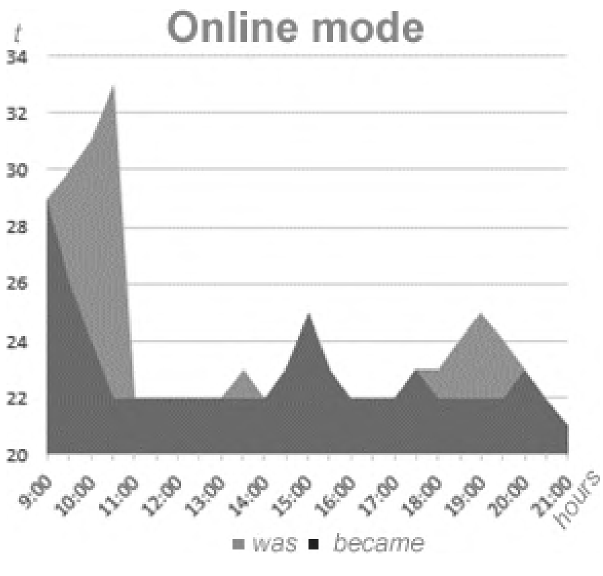

Figure 5. Temperature control according to user commands.

The system provides for critical situations. For example, an IoT temperature sensor failure or an erroneous user command that can lead to a dangerous change in indoor temperature. Therefore, protection mechanisms have been implemented, such as automatic temperature change and notification of the occurrence of a problem.

3. Conclusions

This paper investigated the functionality of chatbots for indoor temperature control using Internet of Things (IoT) systems. The paper analyzed modern programming languages used in IoT systems, and considered the architecture and algorithms of the proposed system.

The system integrates a chatbot driven by natural language processing with temperature sensors, air conditioners, and a database. Users can issue commands through the chatbot to regulate the temperature, monitor the current status, and receive notifications of critical situations. The main components of the system are modules for a chatbot, controller, IoT hub, and IoT sensors. The core of the chatbot is the spaCy library for natural language processing. The system uses the Python programming language, PostgreSQL for the database, and the AWS IoT Core platform. The system has been successfully tested in a real-world environment of a large hangar. The chatbot has demonstrated the ability to autonomously maintain the desired temperature, interact with the air conditioning system, and respond to user commands. The system also has mechanisms to protect against critical situations, such as sensor failures or dangerous commands from users.

The research demonstrates the potential of chatbots as an intelligent user interface for IoT systems, combining automated control and convenient human interaction. The developed system is flexible and scalable, which opens up prospects for its further improvement and implementation in various fields.

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Technology of castings restoration by casting alloyed thermite melt onto the surface

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Technology of castings restoration by casting alloyed thermite melt onto the surface

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Abstract. The study describes the process of forming a functional layer of thermite melts on the surface of castings. The chemical composition of thermite mixtures, technological parameters of various processes of surface alloying of castings, structure and mechanical properties of alloys, and operational properties of castings were examined at various stages of the development of energy-efficient technology for creating a functional surface of a given thickness. The described technology of surface alloying of castings by obtaining functional layers from thermite melts refers to the aluminium-thermite method of obtaining a melt with its subsequent casting on the surface of castings to form a wear-resistant functional layer or direct casting of castings. Characteristic features of the technology are: the use of cheaper internal chemical energy of the interaction of reagents to produce melts, instead of external electrical energy; simplicity and cheapness of the equipment used; obtaining various grades of alloys; high speed of processes in metal synthesis; high productivity of the process of manufacturing or repairing castings.

1. Introduction

The task of improving the wear resistance of chromium cast iron parts includes choosing the chemical composition of a wear-resistant alloy depending on the operating conditions of the casting, the technology of its production, and optimal casting modes.

The choice of materials depends on the manufacturing technology of castings, requirements for mechanical and operational properties, production costs, etc. In conditions of abrasive wear in a neutral environment, chromium-molybdenum cast irons have maximum wear resistance [1,2]. The high cost and scarcity of molybdenum restrain their widespread use.

High chromium cast iron with carbides M_7C_3 is inferior to chromium-molybdenum and chromium-manganese cast iron with a martensitic structure. Nevertheless, chromium-nickel wear-resistant cast iron EN-GJN-HV600(XCr23) DIN EN 12513:2000 is still very widely used to manufacture many fast-wearing processing equipment castings [3]. Under conditions of hydroabrasive wear at small angles of attack, the higher the wear resistance, the more carbides are contained in the alloy.

In the production of a substantial number of cast parts that work in conditions of intense wear, high temperatures and aggressive environments (heat power, metallurgy, mining-processing and chemical industry), their manufacturing technologies using bulk metal alloying [4, 5] are mainly used, which is often not effective since only a tiny thickness of such parts is a working surface and is being worn out. This leads to unjustified costs of expensive high-alloy alloys and an increase in the cost of casting. The production of castings with different properties of individual parts is conducted in different ways: sequential or simultaneous pouring of different melts into a mould, pouring melt on a solid billet, etc [6, 7]. Most of these technologies require the simultaneous melting of alloys of different chemical compositions in separate melting units and additional melt processing operations, complicating the technological process of manufacturing castings with functional layers.

Also, considerable attention of researchers is paid to the development of technological processes for manufacturing castings with surface functional layers, in particular, wear-resistant ones, the properties of which are given by alloying them [8, 9]. Surface alloying of castings by applying alloying coatings to the inner surface of the mould allows obtaining a surface layer with differential properties of no more than 10 mm. Applying a surface alloyed layer to castings by exothermic surfacing in the field of centrifugal forces or electroslag surfacing allows obtaining a functional layer of any size, however, these methods require complex equipment [10–13].

The use of metallothermy methods for the synthesis of melts of a given chemical composition and the production of castings with alloyed functional layers is a promising direction for the development of existing technologies since this ensures a certain autonomy, simplicity and cheapness of technological equipment, high productivity, dismisses the need for powerful sources of electricity, etc [14–19]. However, the problem of predictability of the structures of synthesised alloys and controllability of a substantial part of their physical, mechanical, and service properties limits the use of metallothermal processes in the industrial practice of foundries.

Thus, this study, which is aimed at developing the theoretical and technological foundations of surface alloying of castings by obtaining and casting functional layers from thermite melts, is relevant.

2. Goals and objectives

The purpose of the study is to substantiate the technological parameters of obtaining and casting chromium-alloyed functional layers from thermite melts for the manufacture and reproduction of castings.

Achieving this goal involves solving the following tasks:

- set the parameters for forming the structure of the functional layer and the fusion zone with the casting body (base) depending on the controlled technological parameters;
- develop recommendations for the technological process of surface alloying of castings by forming a functional layer with the specified properties.

3. Materials and methods

Exothermic alloying is the process of obtaining a casting from a liquid thermite metal of a given chemical composition, as a result of an exothermic reaction of a reducing metal with metal oxide.

The standard exothermic reaction proceeds with a substantial release of heat and has the following form:

$$\mathrm{MeO} + \mathrm{R} = \mathrm{Me} + \mathrm{RO} - \mathrm{Q},$$

where MeO – metal oxide; R – reducing metal; Me – metal reduced from the oxide; RO – oxidised reducing metal; Q – thermal energy released during the reaction.

Aluminium has a higher affinity for oxygen than most other metals. It is also relatively cheap and non-deficient, so it is a preferred reducing metal.

As a metal oxide, iron oxides, iron scale, or iron ore are most often used. Scale includes several iron oxides: FeO (iron oxide) – with 22.2% of oxygen, Fe_3O_4 (nitrous oxide-iron oxide) – with 27.58% of oxygen, Fe_2O_3 (ferric oxide) – with 30.0% of oxygen.

During the combustion of the thermite mixture, the following exothermic reactions occur:

$$2Al + 3FeO = 3Fe + A1_2O_3 - 0.835 \cdot 10^6 \text{ J/kg of the mixture},$$

$$8Al + 3Fe_3O_4 = 9Fe + 4Al_2O_3 - 3.239 \cdot 10^6 \text{ J/kg of the mixture},$$

$$2Al + Fe_2O_3 = 2Fe + A1_2O_3 - 0.830 \cdot 10^6 \text{ J/kg of the mixture}.$$

The reaction products are iron reduced from oxides (thermite steel) and aluminium oxide (thermite slag).

When obtaining a melt from thermite mixtures, it is important from a practical standpoint to ensure the necessary chemical and fractional composition, various physical properties, and the maximum yield of a suitable exothermic composition per unit mass. Regulation of the chemical composition of the resulting metal determines the need to use various ferroalloys, ligatures, and carburiser in the composition of thermites, which affect changes in the temperature of reaction products. The more impurity elements contained in the resulting alloy, the more components should be in the thermite composition. This reduces the value of the peak temperature surge of the exothermic process and the residence time of the resulting system at different temperatures. In some cases, when obtaining certain grades of alloys with a low content of impurity elements in the composition, this is positive since the carbon monoxide of the elements decreases, gas release decreases, and the yield of the metal phase increases.

The following components were used to prepare the compositions of thermite mixtures:

- aluminium alloy cuttings of 0.2-0.5 mm fraction with chemical composition: Al = 98.627%; Mn = 0.019%; Si = 0.855%; Cr = 0.016%; Ni = 0.004%; Cu = 0.018%; Fe = 0.462%.
- iron scale powder of 0.2-0.5 mm fraction with chemical composition: C = 0.150%; Mn = 1.188%; Si = 2.960%; S = 0.030%; P = 0.030%; Fe = 71.500%; Al = 0.697%; Ni = 0.188%; Cr = 0.173%; Cu = 0.444%; O_2 = 22.639%.
- ferromanganese powder of fractions up to 0.4 mm with chemical composition: Mn = 78.050%; C = 6.990%; Si = 0.790%; P = 0.500%; S = 0.008%.
- ferrochrome powder up to 1 mm fractions with chemical composition: Cr = 79.500%; C = 0.110%; Si = 1.830%; S = 0.028%; P = 0.030%.
- chrome powder up to 0.3 mm fractions with chemical composition: Cr = 99.0%.
- grits of steel fractions of 1-3 mm with chemical composition: C = 0.180%; Mn = 0.520%; Si = 0.210%; S = 0.021%; P = 0.028%; Ni = 0.010%; Cr =0.110%; Cu = 0.220%.
- powder of graphite electrodes up to 0.063 mm fractions with chemical composition: C = 99.8%; rest – impurities.
- to obtain the reaction initiator consisting of dispersion aluminium and scale, aluminium powder of the PAP-2 brand was used and ground scale of a fraction less than 0.1 mm.

The technology of preparing compositions of thermite mixtures is reduced to the following: scale is calcined to remove lubricants, crushed, subjected to magnetic separation, and separated by fractional composition to obtain an average particle size of 300-400 microns. Powders of aluminium, ferromanganese, ferrosilicon, ferrochrome, chromium, and iron are used for the preparation of metallothermite charges without prior preparation.

When preparing the mixture, no binders are used, which only worsen the combustion process since a thin film appears on the surface of the grains of the components of the thermite mixture, which exacerbates the conditions for redox reactions. One of the main requirements for the initial charge is its uniformity, which determines a uniform combustion front. Therefore, it is necessary to perform high-quality mixing of charge materials. Mixing of thermite charge components was conducted in a drum-type mixer, its application is determined not only by the simplicity of the equipment but also by the high quality of mixing and maximum safety. At a speed of 0.5-0.6 reps, the mixing-pouring mode, in this case, is the most effective. Mixing lasted 5-10 minutes.

The production of castings with functional layers of thermite melts involves compliance with the production process, developed by us, which is shown in figure 1.

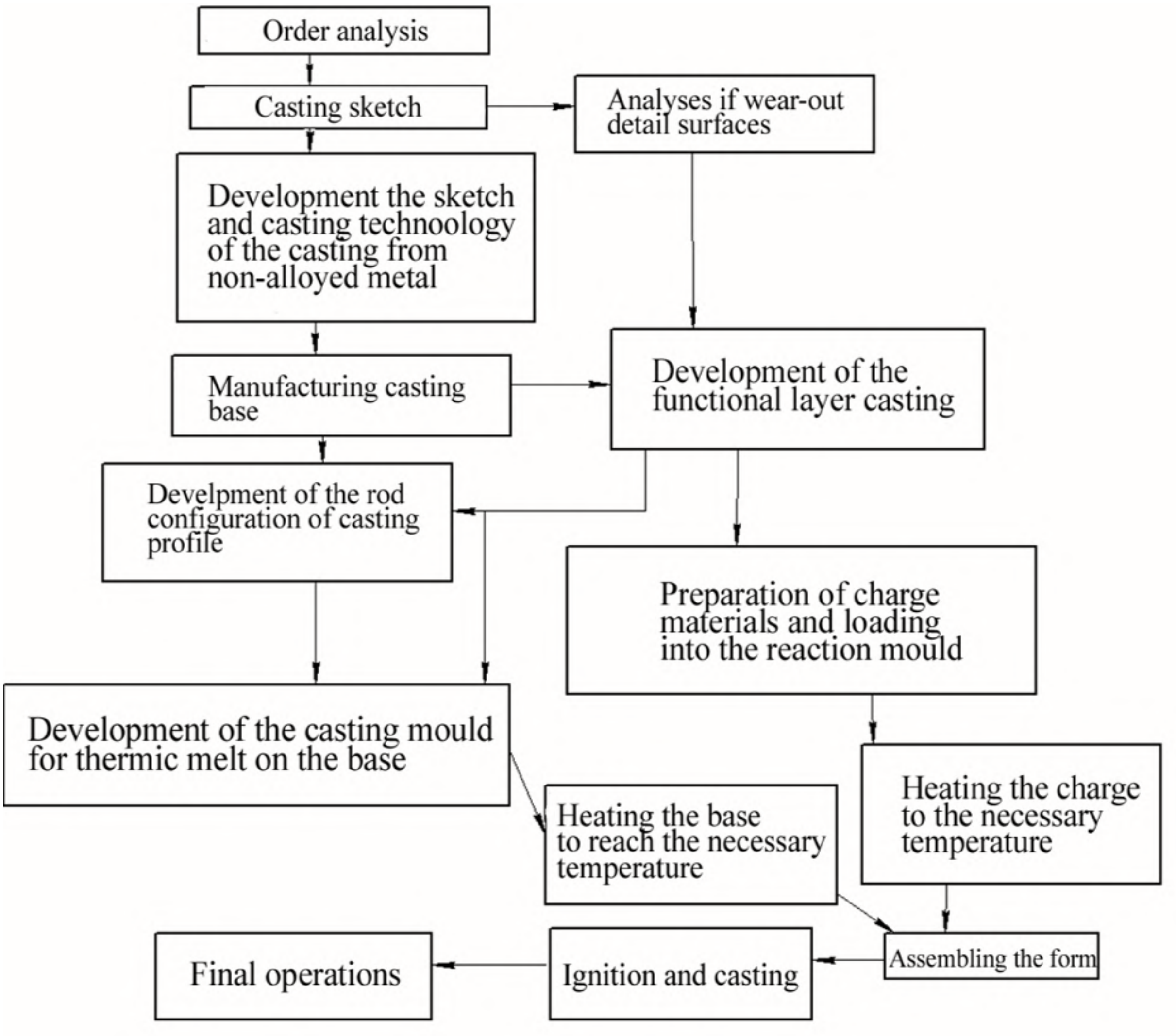

Figure 1. Diagram of the production process for manufacturing castings.

4. Results and discussion

The technology of casting thermite melts provides for the production of both profile castings and planar ones. The assembly mould diagram for surface alloying of profile castings is shown in figure 2, and planar ones – in figure 3. The technology of obtaining planar castings involves loading the charge onto the base, so the casting mould is made without a drain-feed system. After the thermite melt is synthesised, it is deposited on the casting base and forms a functional layer.

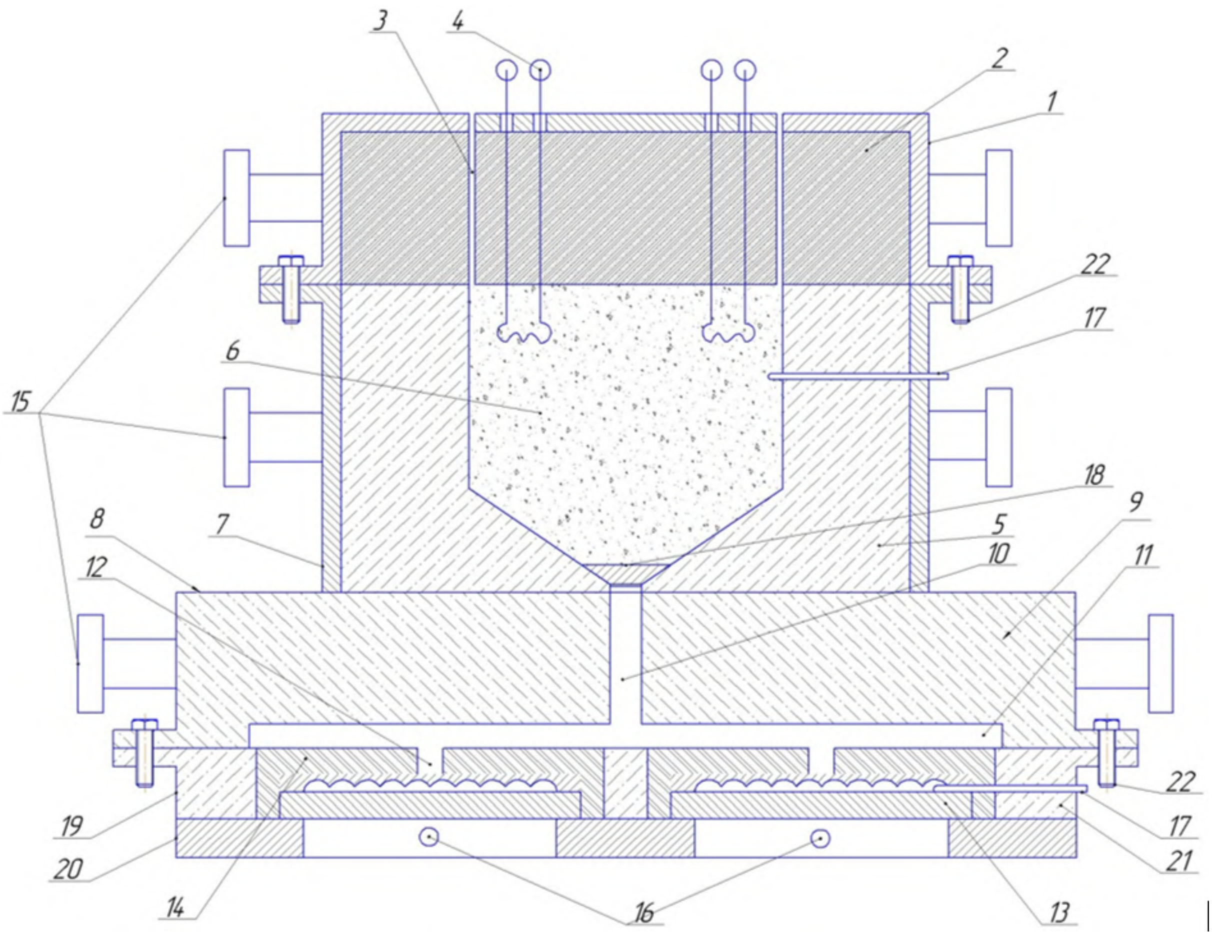

Figure 2. Injection mould assembly: 1 – frame of the top of the reaction mould, 2, 5 – sand-graphite moulding mixture, 3 – vapours, 4 – tungsten spiral, 6 – thermite charge, 7 – frame of the bottom of the reaction mould, 8 – frame of the top of the injection mould, 9 – moulding mixture of the frame of the top, 10 – standpipe, 11 – slag trap, 12 – feeders, 13 – casting base, 14 – rod, 15 – trunnions for transportation, 16 – gas burners, 17 – thermocouple, 18 – aluminium stopper, 19 – frame of the bottom of the mould, 20 – heating plate, 21 – moulding mixture of the frame of the bottom, 22 – centring and guide pins.

In the manufacture of complex-profile castings, a cast base is installed on the heating plate for casting an alloyed functional layer on its surface. The heating plate serves as a submodel plate and is part of the casting base heating system.

Under the influence of high temperature, the aluminium plug that blocks the casting passage melts and the thermite melt is poured through the valve feed system into the cavity between the rod and the casting base, where an alloyed functional layer is formed.

A rod of the appropriate configuration is made to obtain a functional layer of a complex profile. The composition of the core mixture is shown in table 1.

The surfaces of the rods in contact with the melt are painted with a spray gun with graphite-based paint with a layer of 0.2-0.3 mm to ensure stable roughness and prevent burning. The thermite charge is calculated according to the required volume of the cast layer, considering the density of powder shakedown and the yield of a suitable melt. The charge is filled in layers and compacted on the vibrating table for 1–3 min to prevent the formation of hollow arches.

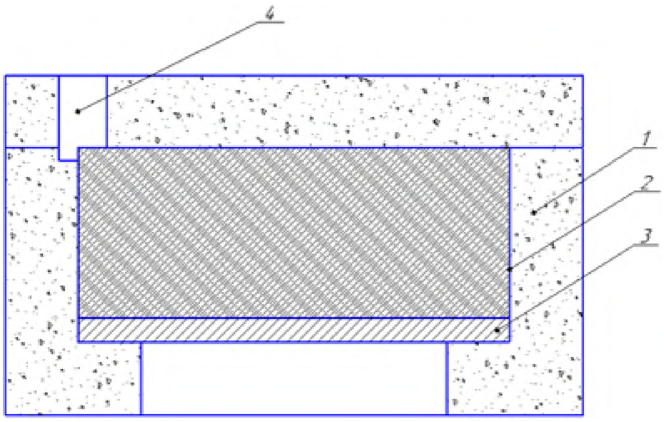

Figure 3. Mould-reactor with an open metal base in the lower part: 1 – moulding mixture; 2 – thermite charge; 3 – metal base; 4 – hole for ignition of thermite charge and gas discharge.

Table 1. Composition of the core mixture.

Name of components	Brand, class	Content in the mixture, %
Quartz sand	2K1O302	11-13
Circulating mixture	–	85
Moulding clay	P1T1K	4-2

The bulk density of aluminium powder is $0.96 \cdot 10^3$ kg/m^3, iron $2.9 \cdot 10^3$ kg/m^3, chrome – $2.5 \cdot 10^3$ kg/m^3, rolling scale $2.1 \cdot 10^3$ kg/m^3. The density of the bulk charge can vary from 1.8 to $2.1 \cdot 10^3$ kg/m^3 depending on the composition, and after the shakedown increases by 22-25%.

The mass of the thermite mixture required to obtain a high-quality casting is based on the total mass of the casting with slug and the drain-feed system, including the mass yield of the thermite alloy during the reaction and is determined by the formula:

$$m_m = \frac{100 \cdot m_c}{W}$$

The volume of this thermite mixture is calculated by the formula:

$$V_m = \frac{100 \cdot m_c}{W \cdot \rho_m}$$

where m_c is a gross mass of castings with slug, kg; W – yield of usable metal, %; ρ_m – bulk density of the thermite mixture kg/m^3.

The resulting compacted mixture is filled in layers into a reactor mould. A tungsten spiral is installed in the upper part of this mould to initiate combustion, and its high-quality contact with the charge is ensured.

After that, the reaction form is fed into a heating furnace to heat the mixture to a temperature of 873 K, which determines satisfactory qualitative and quantitative indicators of the thermite melt [20]. A heated reaction chamber with a thermite charge is installed on top of the mould and fixed above the standpipe, connecting the casting passage and the plug.

Burning of the thermite charge begins from the stage of its ignition with a hot tungsten spiral, the temperature must be at least 1573 K. This heat quickly heats up the surface layer of the charge and excites a rapid exothermic reaction in it. The resulting combustion front extends to the bottom.

Determination of the average volume velocity of the combustion front (kg/m^2·s) was conducted based on calculating the time (t_c) burning of a certain mass of thermite mixture m_m from the beginning of the reaction to its complete completion from a certain area (S_c) by the formula:

$$v_c = \frac{m_m}{S_c \cdot t_c}$$

The temperature of the resulting melt is determined by the composition of the thermite charge and the amount of metal powders – fillers. It is important that the melt has a temperature higher than the melting point of aluminium oxide (corundum, reaction product) since this ensures that there is no layer of slag inclusions in the transition zone between the functional layer and the casting base. The low temperature makes it impossible for the surface of the casting base to alloy since the thermite melt, when it comes into contact with a relatively cold metal, cools quickly. Heating the casting base to a temperature of 873 K using injection burners with a gas/air mixture or induction devices helps to obtain a defect-free strong metal bond in the transition zone. The optimal heating temperature of the casting base is determined by the temperature and time of the melt interacting with it, the maximum thickness of the resulting functional layer, and the wall thickness of the casting.

In addition to obtaining a high-quality fusion zone of the casting base with the thermite melt of the functional layer, the temperature-time regime should ensure that gas bubbles formed during thermite reactions come to the surface. The time t_{min}, required for the gas bubble to escape from the melt of the function layer was determined according to the following scheme. It is assumed that the bubble starts moving from an arbitrary point N in the fusion zone (figure 4) and stops at a point M at a distance r from a point on the surface of the melt mirror that corresponds to the maximum thickness of the resulting layer.

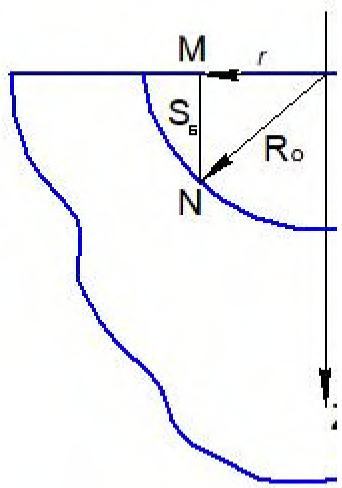

Figure 4. Calculation scheme for the time t_{min} of release of a gas bubble from the thickness of the thermite melt.

A right triangle formed by a segment MN is considered, which is numerically equal to the path S_b that the bubble travels; distance r between M and the center of sphere, inscribed in the heat node of cast layer; radius of this heat node R_0, which limits the local cavern of the defect (wear) at the base. The bubble path is equal to:

$$S_b = \sqrt{R_0^2 - r^2} = R_0\sqrt{1 - \left(\frac{r}{R_0}\right)^2}. \tag{1}$$

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Then, t_{min} required for the gas bubble to escape:

$$t_{min} = \frac{S_b}{v_b}, \tag{2}$$

where v_b – the speed of the gas bubble.

Substituting expression (1) into formula (2), the following is obtained:

$$t_{min} = \frac{R_0}{v_b}\sqrt{1 - (\frac{r}{R_0})^2} \tag{3}$$

The approximate value of the velocity of a gas bubble with a density of 0.00028 kg/m^3 in a melt with a density of about 7.0 kg/m^3 and a density is 0.0029 kg/m · s, depending on its radius (R), by Stocks equilibria is equal to v_b=4820·R^2.

Then, from equation (3), t_{min} relative to any point on the surface of the casting base and the layer thickness can be determined. Solutions to equations (3) for a bubble with a radius of 0.05 mm were obtained using the MathCAD software in the form of a graph (figure 5).

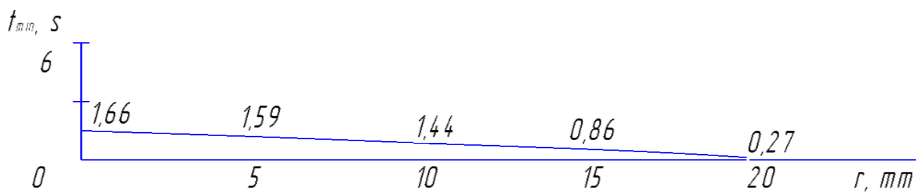

Figure 5. The time t_{min} of exit of a gas bubble with a radius of 0.05 mm at different values of r.

The time of a gas bubble escaping to the melt surface at the deepest point (20 mm) at $r = 0$ is 1.66 s, and when $r = R_0$, is decreased to 0.27 s.

Calculations of the time of movement of gas inclusions of different sizes showed table 2 that in the deepest part of the formed layer (figure 6), all gas bubbles with a diameter of more than 0.03 mm during the melt being in the liquid state (about 20 s [20]) will have time to reach its surface.

Table 2. Time of bubble exit to the surface of the alloyed layer depending on its diameter at different points.

Bubble diameter, D mm	Exit time t_{min} of a bubble at different points of the formed layer, s	
	$r = 0$	$r = R_0$
0.1	1.66	0.11
0.09	2.05	0.13
0.08	2.6	0.16
0.07	3.39	0.21
0.06	4.6	0.41
0.05	6.64	0.66
0.04	10.4	0.98
0.03	18.4	1.43
0.02	41.5	4.5

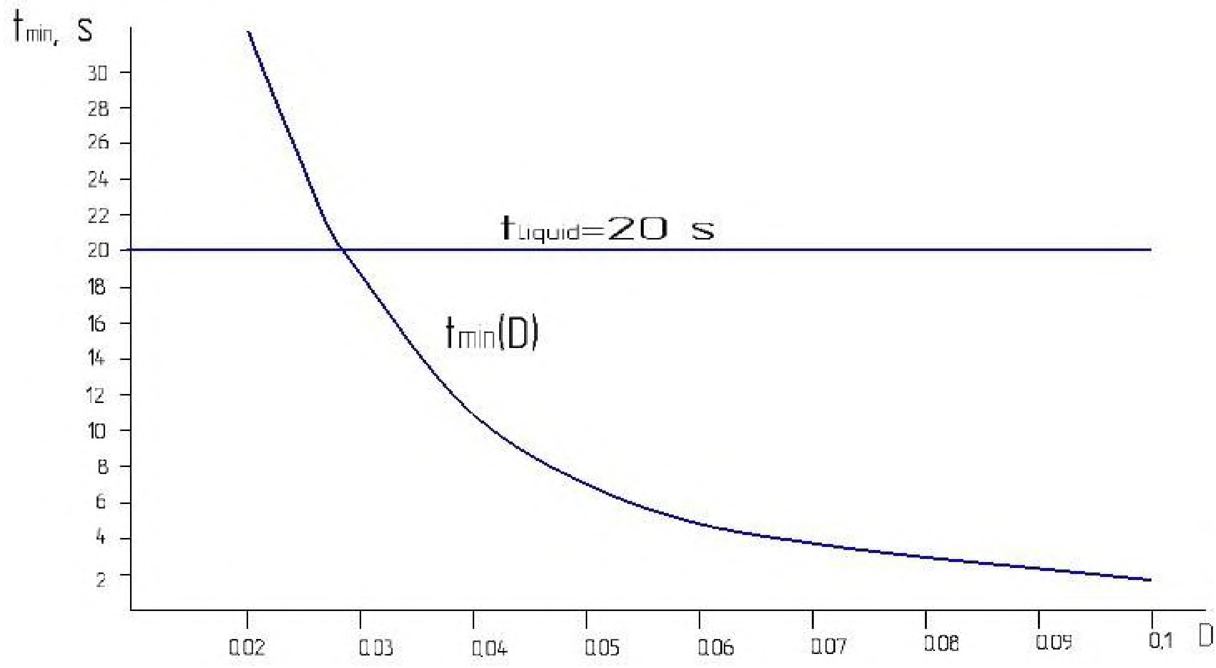

Figure 6. Exit time t_{min} of gas bubbles to the surface from the maximum (20 mm in calculations) depth of the functional layer, depending on the diameter of the bubble.

Near the open interface of the base and the formed alloyed layer at $r = R_0$, all bubbles with a diameter of 0.01 mm or less will exit. Micropores that remain cause a decrease in the density of the functional layer.

Thus, almost all gas bubbles during the time during which the melt is at the solidus temperature, have time to reach its surface. Notably, the above calculations were conducted, provided that the thermite melt is in a stable state and the movement of the gas bubble can be considered laminar. In practice, the formation of a thermite alloyed layer occurs under conditions of strong perturbations, primarily associated with the unstable and turbulent nature of the exothermic reaction. Disturbances that are transmitted to the thermite melt from the reacting components of the charge cause unregulated flows that affect the movement of gas bubbles. This explains the presence of individual pores of small diameter in the functional layer.

Experiments on obtaining a cast with a functional layer were conducted at the Kolbi enterprise (Kryvyi Rih) with a worn-out casting "Front seal disc" (figure 7) – detail of a suction dredge pump 400/40 (8gr-8).

The working surfaces of seal discs wear out due to the contact of solid abrasive particles with the walls of the channels of the flow part.

During the tests, it was attempted to obtain alloyed thermite alloys that are similar in composition to cast iron grades (by ASTM A532) Class 2 type B (C – 1.6-2.4%, Cr – 13-19%) and Class 2 type D (C – 2.4-3.6%, Cr – 19-25%). Based on the results of calculations, the indicators of the melt formation process for various charge compositions (70 kg of scale and 30 kg of aluminium powder) were determined, considering its heating temperature (table 3).

As can be seen from the table 3, reducing the amount of chromium powder for every 10% (relative) and replacing it with iron powder allows increasing the amount of exothermic alloy by 0.9%.

Based on the results of field experiments, it was determined that the highest melt yield (54.77%) can be obtained by heating the charge to 873 K, which was confirmed by the previously

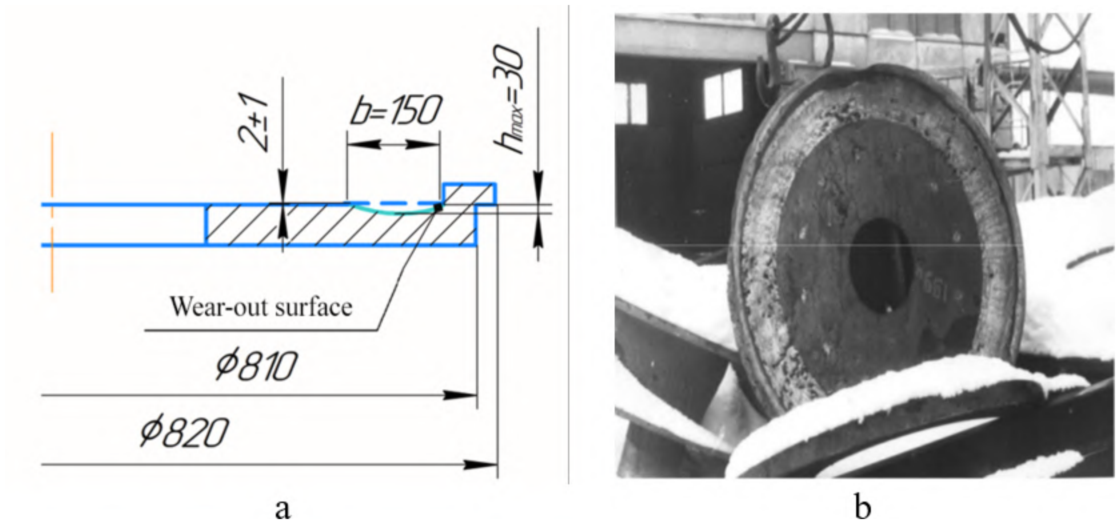

Figure 7. Front seal disc of the 8gr-8 pump: *a* – sketch, *b* – after operation.

Table 3. Initial and effective indicators of the melt formation process.

Experimental charge	#1	#2	#3	#4	#5	#6	#7	#8	#9
Charge heating temperature, K	873	873	873	873	873	873	873	873	873
Approximate alloy grade	SCH10	CHH22	CHH22	CHH16	CHH16	CHH16	–	–	–
Content of metal powders in the charge, % from weight of the thermite mixture									
Cr	–	12.8	10.8	8.8	7.1	9.5	6.5	4.5	3
Fe	35.1	–	–	–	–	9.5	17.5	23	30
Carburiser	5.3	3.8	3.6	3.5	3.4	3	4.3	4.6	5
Estimated amount of charge, kg	140.4	116.6	114.4	112.3	110.5	122	128.3	132.1	138
Estimated amount of melt, kg	76.9	54.6	52.6	50.6	48.9	60.5	65.6	69.12	74.67
Content in the melt, %									
Cr	–	22.5	19.7	16.06	13.94	15.08	9.52	6.25	3.85
C	3.38	3.37	3.32	3.35	3.37	2.4	3.18	3.22	3.24
Al	7.62	11.0	11.3	11.7	12.1	9.9	9.15	8.7	8.0
Melt yield from 1 kg of charge, %	54.77	46.8	45.9	45.0	44.2	49.6	51.1	52.3	54.1
Melt volume from 1 kg of charge, cm3	78.18	66.8	65.5	64.2	63.1	70.8	72.9	74.6	77.2

identified data [20].

5 dm^3 reactor moulds were installed in five places (considering the charge composition and yield of suitable melt) for obtaining up to 1.6 kg of thermite melt on an area of 150×100 mm with an average layer thickness of 15 mm to recreate the planar working surface of the seal disc. The thermite charge was used with different chromium and carbon content to produce a functional

layer similar in chemical composition to the cast iron grades from Class 1 Type A to Class 2 Type D (ASTM A532).

As noted above, due to the justification of methods for determining the temperature-time and qualitative-quantitative parameters of the melt formation process, it is possible to control the temperature and amount of thermite melt formed, its chemical composition, hardness, and relative wear resistance due to different structural and phase states.

Charge#2 was chosen, the chemical composition of which is close to cast iron Class 2 type D to obtain a wear-resistant layer of the entire damaged surface of the seal disc. A special feature of the surface is uneven wear up to 30 mm thick. According to calculations:

- the area of the damaged surface – 3060 cm^2;
- damaged surface volume – 4600 cm^3;
- thermite melt weight – 32.5 kg;
- thermite charge weight – 70 kg;
- required volume of the reactor mould – 30 dm^3.

The restored casting was formed according to the scheme shown in figure 2. The thermite charge and base were heated to 873 K. After that, surface alloying was conducted by casting a thermite melt on the damaged relief surface. The thickness of the wear layer, depending on the depth of wear, ranged from 1 to 30 mm.

Then the slag phase was separated and the resulting layer was mechanically processed to level its surface.

The resulting seal disc was transferred to the mining enterprise for analysis of its service life in industrial conditions.

It is proposed to replace valuable metal powders with powders prepared from metal waste to reduce the cost of casting, namely by crushing deposits of ferroalloys, cast iron, and aluminium cuttings.

Test results of cut-out samples obtained from experimental charges (table 3) at 873 K are shown in table 4.

Table 4. Chemical composition and mechanical properties of functional layers.

Sample number*	Content of elements in the functional layer, %			Number of strengthening in the functional layers, %			Microhardness of castings, MPa	Wear resistance coefficient
	C	Cr	Al	Al_2O_3	Fe_3C	Cr_2C		
2	3.38	22.5	11.0	19.0	9.6	23.0	5580	2.1
6	2.4	15.1	9.9	17.3	9.0	15.5	4170	1.4
7	3.18	9.52	9.15	15.9	28.8	9.8	2200	1.0
8	3.22	6.25	8.7	15.2	34.8	6.5	1740	0.8
9	3.24	3.85	8.0	14.0	39.1	4.0	1068	0.7

* The sample numbering corresponds to the sample numbers in the table 3

Tests showed the same wear resistance of the thermite functional layer alloyed with Cr 9.52% compared to the base cast iron sample EN-GJN-HV600(XCr23).

The addition of chromium to the charge increases wear resistance by increasing the total number of carbide and oxide phases. The improved wear resistance of the prototypes is also associated with the cooling rate of the functional layers, which reached 83°C/s. A high cooling rate during crystallisation changes structural characteristics such as the size of carbides and the relative position of phases. The increased number of non-metallic phases in the functional layers also increases wear resistance, which is associated with the high physical and mechanical properties of corundum. Since the formation of inclusions takes place during the formation of the structure, they have a high cohesion to the entire metal matrix.

A sample obtained from charge#2 was selected due to high wear resistance and microhardness to examine the quality of the connection of the functional layer with the casting base. The sample was cut into two parts. A conventional cutting abrasive wheel turned was identified to be unsuitable, so cutting was performed with a water-cooled diamond wheel. In cross-section, there are no distinctions in the functional layer, the fusion of casting layers is characterised as a defect-free connection zone.

A metallographic section was made from half of the sample, which was examined using an epiquant metallographic microscope. Against the background of the relief of the microstructure without etching, corundum inclusions inside carbides are observed (figure 8 magnification $\times$ 600).

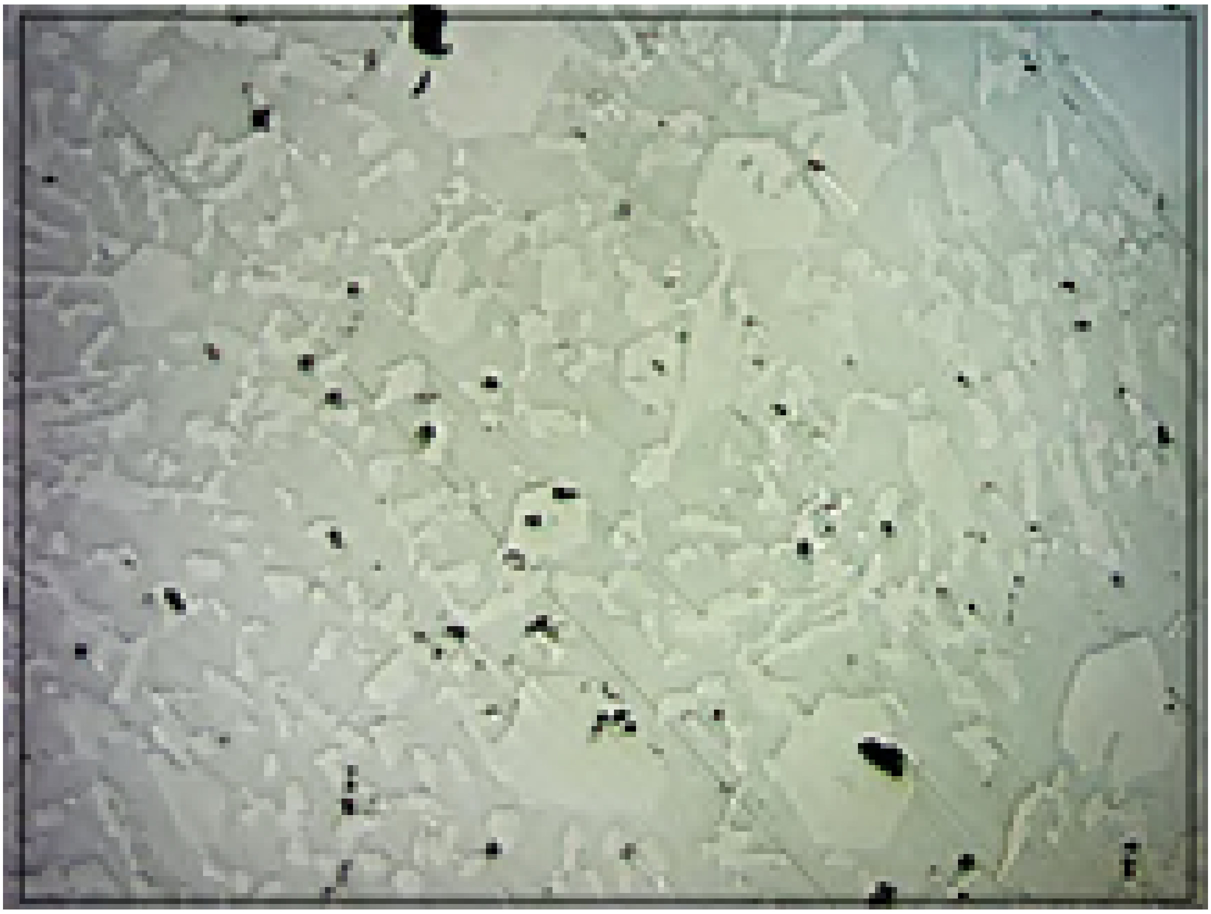

Figure 8. Microstructure of the sample without etching.

Dark inclusions inside carbides are corundum inclusions that provide the effect of modifying the thermite melt. These crystallisation centres contribute to the formation of chromium carbides [21]. The microhardness of individual inclusions is determined by the PMT-3 microhardness meter, which allows accurate measurement of microhardness in the designated zone.

The conducted studies allow concluding that fine-grained chromium carbides are present in the microstructure of the functional layer. Inclusions of chromium carbide with imprints from the diamond pyramid, the microhardness of which is 18540 MPa, are shown in figure 9.

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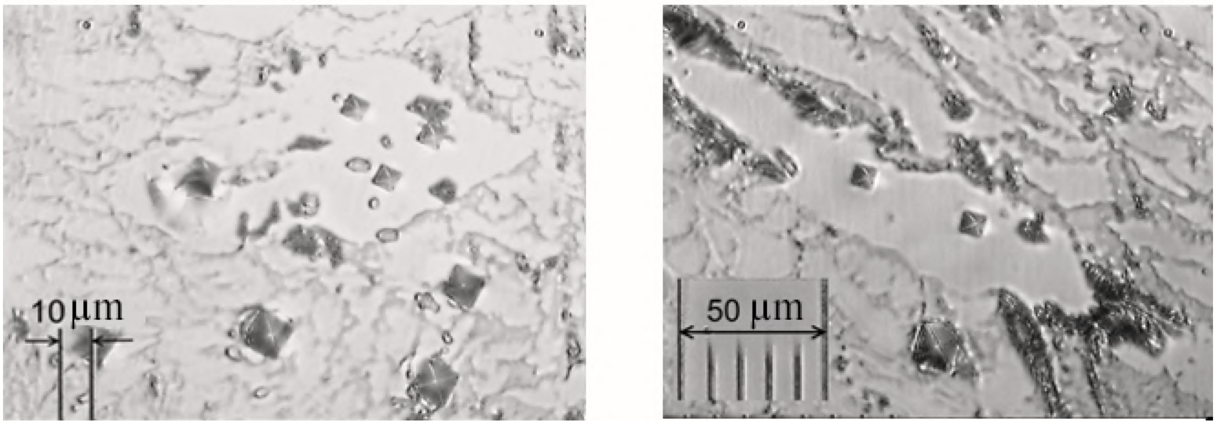

Figure 9. Inclusion of chromium carbide with diamond pyramid imprints.

Examination of the sample after etching in a 4% alcoholic solution of nitric acid showed that the carbide component formed around the corundum prevails against the background of the fragmented relief (figure 10, magnification × 300).

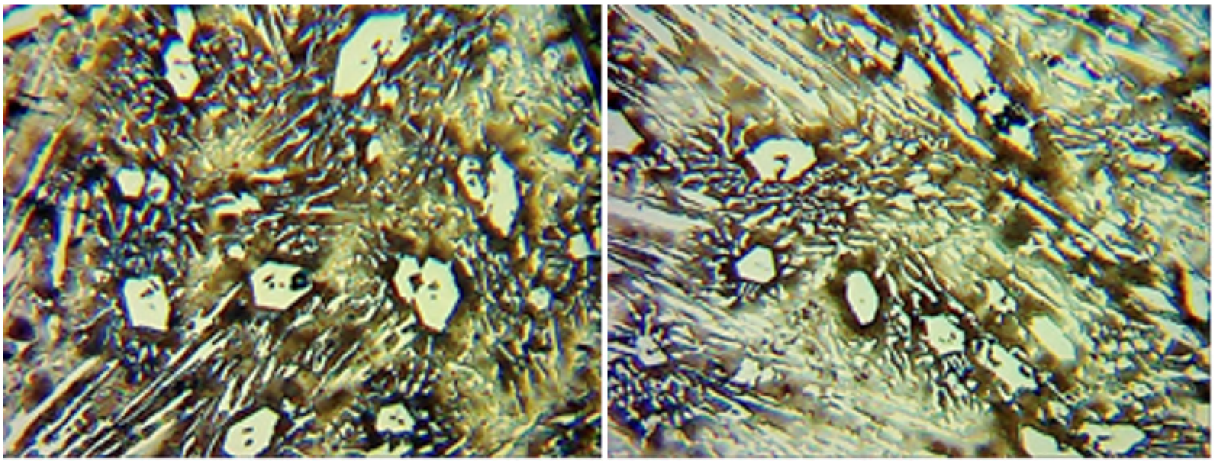

Figure 10. Microstructure of the sample.

5. Conclusions

With a thickness of the formed layer of 20 mm, all gas bubbles with a diameter of more than 0.03 mm during melt being in the liquid state have time to reach its surface. Near the open interface between the main and formed alloyed layers, all gas inclusions with a diameter of up to 0.01 mm will exit its surface.

At a worn-out casting temperature of 873 K and a melt temperature of up to 2500 K, a reliable fusion of a functional layer up to 30 mm thick with a base was observed over the entire surface of the restored disk.

The proposed technology allows the following:

- obtaining a high-quality surface connection zone made of non-alloyed alloy with an alloyed functional layer made of thermite cast iron, close in composition to Class 2 type D (ASTM A532);

- increasing the inter-repair period of casting due to almost 2 times greater wear resistance;
- reducing energy costs in the production of melt by aluminium-thermite method;
- reducing the cost of production.

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IOP Conference Series: Earth and Environmental Science

Sustainable web API evolution: Forecasting software development effort

Sustainable web API evolution: Forecasting software development effort

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Abstract. The study delves into the main stages of the life cycle of software systems, emphasizing the integral role of web APIs within this framework. Notably, we focus on analyzing the structural components of development costs associated with these systems. Our findings reveal a considerable portion of the costs dedicated to sustaining the robust development of the software system. This underscores the importance of forecasting the intensity of various types of requests for system changes, enabling the timely fulfillment of customer requirements and accurate estimation of investment costs throughout the software system's life cycle. To address this need, we propose a method for forecasting costs to support the sustainable development of a software system. This method relies on a hierarchical algorithmic clustering approach applied to retrospective weekly schedules of client requests for system changes. The clustering process is executed separately for each type of change, yielding distinct graphs. Representative graphs within the obtained clusters serve as key elements in predictive calculations. Determining a representative graph for each cluster, along with the corresponding cluster size, enables prediction by adding representative graphs in proportion to the cluster size. Maintaining the correct proportionality is achieved through the implementation of a greedy algorithm. The application of the developed forecasting method to support the sustainable development of the software system is illustrated using experimental data. This approach not only caters to current customer requirements but also ensures a comprehensive estimation of investment costs, offering valuable insights for optimizing the software system's life cycle.

1. Introduction

In today's digitally connected world, web application programming interfaces (web APIs) are indispensable in allowing distributed parts of software systems to communicate with one another. Web APIs are exposed over a network and are often referred to as remote APIs to distinguish them from static ones, which are used to connect software components running on the same machine [1]. In a nutshell, web APIs are rules and protocols for building and interacting with software applications. As Andreo and Bosch have put it, "...we can define APIs as a set of requirements that govern how applications can interact and exchange data and how we want to deliver value to the customers" [2]. Due to the rise of containerization and microservices, web APIs are being used even when communicating components are running on the same machine [3].

Web APIs constitute an essential part of services computing, which has evolved from a technology focused on enterprise interoperability to becoming a key driver in developing the web API economy [4]. According to Basole, "The importance of APIs is particularly amplified with the emergence of the idea of the "everything-as-a-service" (XaaS) paradigm, which envisions business capabilities, products, and processes not as discreet vertical offerings operating individually in silos but, rather, as a collection of horizontal services that can be accessed and leveraged across organizational boundaries" [5]. Today's most prominent web API ecosystem fields are online mapping, e-commerce, social, analytics, finance, and health [5]. The availability of such APIs allows companies to explore and enter markets that were previously beyond their consideration [4].

This paper proposes a method of forecasting web API development efforts given historical data on types of web API changes and their frequency. The web API change classification can be based on the motivating factors (new features, simplification, error corrections), the API elements changed (resources, methods, fields), the actions performed (adding, renaming, removing), or the way the clients are affected (breaking vs. non-breaking, syntax vs. behavior) [6]. The proposed method is based on predicting the number of changes of each type. The cost of a change can be obtained with expert judgment per change type or deduced from historical data if such information exists. In addition, each change should be easily identified as belonging to a particular type. Given such requirements, it makes sense to classify changes both by API elements changed and actions performed based on API syntax definition.

The rest of this paper is organized as follows. Section 2 highlights the importance of web APIs for digitalization in the energy sector. Section 3 emphasizes the need to evolve web APIs. Section 4 presents the related work. Section 5 describes the proposed method. Section 6 presents conclusions and future work directions.

2. Web APIs in energetics

In the field of energetics (energy-related systems and technologies), web APIs play a crucial role in facilitating data exchange, communication, and integration among various energy-related applications, services, and platforms. Here are some common uses of web APIs in energetics:

- Energy Data Access:
  - Retrieving real-time or historical energy consumption data.
  - Accessing information about energy production, storage, and distribution.
- Renewable Energy Integration:
  - Integrating with weather APIs to incorporate real-time weather data for better renewable energy production forecasts.
  - Accessing APIs that provide information about solar and wind patterns.
- Grid Management:
  - Interacting with APIs to monitor and manage energy grids efficiently.
  - Accessing grid-related data, such as load balancing, demand response, and outage information.
- Smart Home and Building Automation:
  - Integrating with APIs for smart home devices to optimize energy usage.
  - Connecting with building management systems to enhance energy efficiency.
- Energy Market Information:
  - Accessing APIs to retrieve information about energy prices, market trends, and trading data.
  - Interacting with financial APIs for energy-related investments and transactions.
- Electric Vehicle Integration:
  - Connecting with APIs to monitor and manage electric vehicle charging stations.
  - Accessing data related to electric vehicle battery status, usage, and charging patterns.
- Energy Efficiency and Monitoring:

  - Utilizing APIs for energy monitoring and reporting tools.
  - Integrating with energy analytics platforms to optimize energy consumption.
- Environmental Impact Assessment:
  - Accessing APIs for environmental data to assess the ecological impact of energy production and consumption.
- Policy and Regulation Compliance:
  - Connecting with APIs to stay updated on energy-related policies and regulations.
  - Accessing compliance-related information and reporting tools.
- Collaboration and Research:
  - Sharing data and research findings through APIs for collaborative energy research.
  - Creating interoperability between different energy-related research platforms.

Web services allow interconnecting smart houses, smart grids, and energy service providers [7]. Web APIs are indispensable to a smart city solution in facilitating energy-related data collection, aggregation, and consumption [8]. As a mechanism for handling real-time, online, and historical energy data, web APIs can support interoperability in smart cities, facilitate decision-making for energy sustainability, enhance energy prosumption operations, and improve efficiency in smart grids [9]. A district energy management system can provide APIs that enable energy suppliers and facility managers to continuously oversee and uphold the energy distribution network [10].

For smart cities to achieve a sustainable energy future, using electric vehicles when implementing transportation services is crucial. Web APIs can be instrumental in integrating various mobility solutions provided by different stakeholders in urban transportation, which helps reduce costs and create value-added services [11]. When implementing automation, management, and monitoring of energy consumption for smart homes, web APIs facilitate the exchange of data between smart home services and applications for controlling home devices, efficient energy scheduling, and integration with smart city infrastructure [12]. Household energy consumption can be reduced by building applications powered by web APIs that forecast electricity bills and inform users [13]. By leveraging web APIs, stakeholders in the energetics sector can enhance the interoperability of various systems, improve data accessibility, and foster innovation in the development of energy-related applications and solutions.

3. Web API evolution

Web APIs must be initially developed and continuously improved like any other part of a software system. At first glance, the improvement effort should be insignificant. If an API covers the needs of its clients, there is no reason for it to evolve. Nevertheless, that rarely happens in reality. As demonstrated by a prior study, web APIs are still being updated for a long time after creation [14]. When an API is released for the first time, its developers may still need to obtain all the requirements and gain more knowledge of the domain it addresses. That is the reason why an API is often imperfect at launch. Even an initially adequate API can eventually become insufficient or obsolete as new concepts within the domain emerge, legal regulations change, or clients request additional features. According to previous research, new feature requirements and usability are the most significant reasons static APIs change [15]. Those same reasons are valid for web APIs. In addition, the changes can be made to accommodate technological advancements, address bugs, enhance security, or even unintentionally during code refactoring. So, web APIs constantly evolve to prevent themselves from becoming obsolete.

The need to constantly evolve web APIs matches the conclusions of Zarnekow and Brenner, who have found that most of the life cycle costs for a software system occur after the system has been put into production [16]. According to their research, the life cycle of a software system has four stages: planning, initial development, production, further development, and shut-down. Requirements analysis and design are performed during the planning stage. The initial development consists of building, testing, and deployment. The production stage includes system operation, support, and maintenance (e.g., fixing errors). The purpose of further development is to improve the system functionally. Finally, the system shuts down, often replaced by a newer one. The authors have shown that, given a production time of 5 years, the recurring costs of production and further development were 79% of all the total costs on average [16]. Those results indicate how important it is to predict the cost and schedule of further software development. Such estimation is required for project budgeting, analysis of risks and tradeoffs, planning and controlling the project, and analysis of investments into software improvements [17].

Since web APIs have become an essential part of many software systems, predicting and estimating development efforts to support their sustainable evolution while being in production is getting more relevant than ever. In order to plan months ahead and effectively allocate resources, project managers need to know how often web APIs will change and what development effort will be required to perform such changes, even before the requirements for those changes have been received.

4. Related work

In order to forecast software development efforts for a particular time interval, one needs to predict the distribution of change requests and then estimate the effort for each change. The first part can be solved with a time series forecasting model.

Goulão et al. built an ARIMA model that could predict maintenance and improvement requests in the Eclipse project based on data from its change request tracking system [18]. The model had been trained on seven years of request history and could predict change requests over 12 months. In particular, the model included means to identify seasonal patterns, which helped to provide better accuracy. The independent variable of the model was a timeframe, and the dependent variable was the number of changes, so the model could not differentiate between types of changes.

As an alternative to ARIMA models, Saini and Kaur explored using a computational method based on fuzzy time series to predict the number of commits into source control management repositories in several open-source software projects [19]. The authors used the number of commits per month as a metric to analyze 17 years of evolution for seven projects. The prediction accuracy was better when compared to the one of the ARIMA models. While the method could predict how active a project development was, the commits were not classified in any way.

Kalouptsoglou et al. compared the performance of traditional statistical methods and deep learning models in predicting the number of vulnerabilities in five large software projects [20]. For each project, the monthly number of vulnerabilities was forecasted for 24 months ahead based on previous project vulnerabilities for about 20 years. The authors used single and triple exponential smoothing, an Autoregressive Integrated Moving Average (ARIMA) model, Croston's method, a Multi-Layer Perceptron (MLP) model, a Recurrent Neural Network (RNN) model, and a Convolutional Neural Network (CNN) model. The results showed that all the methods had similar predictive power. However, there were projects for which deep learning models performed better. Vulnerabilities in some projects were more challenging to predict than in others. A notable property of vulnerability time series is that vulnerability occurrences are intermittent, i.e., they fluctuate significantly, and many zero values exist.

An effort has to be estimated for each change predicted by the time series forecasting model. There are many methods for software development effort estimation (SDEE). According to a recent review, they can be based on expert knowledge, size, model, analogy, regression, optimization techniques, fuzzy logic, machine learning (ML), and artificial neural networks (ANN) [21]. Expert-based methods include the Delphi technique, Planning Poker, top-down, bottom-up, and rule-based estimation methods. Size-based methods calculate project size in function, use-case, or story points. Model-based methods (COCOMO, COCOMO II, SLIM, SEER_SEM, WBS) are calibrated on previous projects and rely on such factors as the activities covered and attributes of software, computer, personnel, and project [17]. An advantage of such analogy-based methods as Case-Based Reasoning (CBR) is that it is easy to understand the reasoning behind the result. Many regression methods and related techniques are used for SDEE, e.g., simple and multiple linear regression, stepwise regression, Stochastic Gradient Boosting (SGB), and Support Vector Regression (SVR). Multiple optimization techniques such as genetic algorithms (GA), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC) can be employed to obtain more precise estimates. Fuzzy logic methods can deal with imprecise and missing data. The most popular ML methods are support vector machine (SVM) and such tree-based ones as Decision Tree (DT), Classification and Regression Tree (CART), and Random Forest (RF). Artificial neural networks, such as Multi-Layer Perceptron (MLP), General Regression Neural Network (GRNN), Cascade Correlation Neural Network (CCNN), and Radial Basis Function Neural Network (RBFNN), are becoming more popular because they can automatically extract features and capture complex dependencies in data [21].

One of the recent trends is combining several methods in order to obtain better estimates. For example, Case-Based Reasoning (CBR) weights can be optimized using Particle Swarm Optimization (PSO), a method inspired by the social behavior of birds and fish. A study exploring this approach demonstrated that the PSO method outperforms traditional methods in convergence rate and learning efficiency [22]. Another research proposed two architectures of artificial neural networks based on Taguchi's method using such COCOMO attributes as scale factors, cost factors, and software size [23]. According to the paper, clustering projects from different datasets and data fuzzification significantly enhance the efficiency, reliability, and accuracy of SDEE [23]. Even mature methods can provide better results when combined with artificial intelligence approaches. It was reported that integrating a Fuzzy Inference System (FIS) with COCOMO II enhanced model results by introducing fuzziness into estimating size, cost drivers, and scale factors [24]. The authors of another study proposed a heterogeneous ensemble estimation model combining several models such as Use Case Point (UCP), Expert Judgement (EJ), and Artificial Neural Network (ANN) [25]. The study demonstrated that the ensemble technique performed better than separate estimation methods [25].

There is also a challenge of properly integrating effort estimation methods into the practices of agile software development methodologies, which still rely on expert-based effort estimation, despite that ML methods are being used more often than before [26]. An example of such an integration is a model using Bayesian networks to improve effort estimation accuracy for agile teams [27]. In that work, the author identified factors that influenced the effort needed. These were the nodes of a directed acyclic graph and belonged to either teamwork quality or user story characteristics [27].

The papers analyzed consider software development in general without depending on characteristics specific to estimating changes in web APIs. When estimating future changes to web APIs, obtaining the exact number and type of historical changes from API change logs or a version control system storing API definitions may be possible. Having separate data for each type of change should provide better accuracy for predicting changes and estimates of each type of change. The methods used to build a forecasting model need a lot of historical observations for an extended period to predict future changes. That is not the case with web APIs, which usually do not change daily and do not have a history of more than several years. It means another approach to forecasting web API changes must be used. The SDEE methods mainly estimate concrete work when the factors influencing the effort are already known. That makes them of limited use when estimating a typical change that is likely to happen in the future. Nevertheless, most of them can still be used to some extent.

5. Forecasting software development work effort

This research aims to find a way for project managers and stakeholders to predict the effort needed to support web API evolution. In order to manage resources efficiently, it is crucial to estimate the total work for a significant future period and see how the work may be distributed over that period. Since most web APIs do not have to be changed each day, it is impossible to build a predictive model that gives an accurate daily effort estimate for the next quarter or year if the only data available is a list of historical changes. However, building a representative model that captures the underlying patterns and trends is feasible. The proposed method can be used to forecast quarterly or even yearly efforts and understand how future work may be distributed. While that illustrative distribution cannot be used to estimate work effort for a particular day, it will be helpful to assess the expected surges of demand for web API improvements and be ready to invest the time of software engineers into such changes.

In order to demonstrate the proposed method, a representative model based on Stripe API has been built. First, the API changes for three years, from November 18, 2020, to November 17, 2023, were collected from the Stripe API changelog [28]. The distribution of the changes is shown in figure 1.

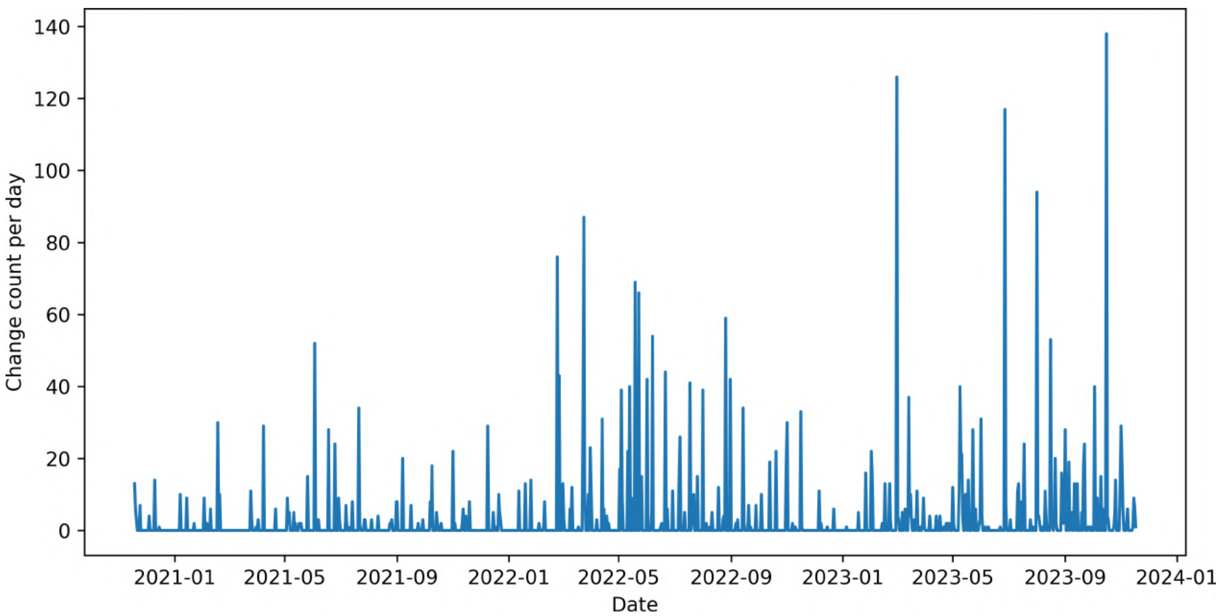

Figure 1. Historical API changes.

In order to demonstrate the proposed method, a representative model based on Stripe API has been built. First, the API changes for three years, from November 18, 2020, to November 17, 2023, were collected from the Stripe API changelog [28]. The distribution of the changes is shown in figure 1.

Second, the changes were classified based on the API elements modified and actions performed. Regardless of whether the method's input or output messages were modified, adding new fields was considered the same type of change because of close semantics and similar implementation complexity. The field removal changes were grouped in the same way. Similar reasoning was applied to the category of field type changes, which includes cases when the actual field type has changed and when field optionality or nullability has changed.

Next, each change type was estimated based on the expert opinion of the authors because the historical data on the work effort spent implementing those changes was unavailable. Any SDEE method can be used to estimate the effort of implementing changes of each type, provided the necessary data related to the project is available. Table 1 lists all the change types discovered, along with the number of changes and effort estimation for implementing a new change of the corresponding type.

Table 1. Change types.

Change type	Historical change count	Effort estimate, person-hours
New resource added	46	100
Resource removed	12	50
New method added	69	20
Method removed	22	10
New field added	1423	10
Field removed	74	5
New enum value added	1338	5
Enum value removed	99	5
Field type changed	343	5

Since historical data can show trends and seasonality, it must be normalized to be useful for forecasting purposes. For example, the demand for web API changes can increase as the number of web API clients grows. However, it is hard to find the exact trends or seasonality in the data collected because, as figure 1 shows, the data is sparse, so three years is insufficient. Because of that, a simple approach was chosen. The changes were counted for each year starting November 18. Also, adjustment factors were calculated as quotients of the change count for the last and each year. The adjustment factors were used in further calculations to normalize historical data by multiplying the change count by the corresponding adjustment factor. Table 2 lists the yearly change counts and adjustment factors.

Table 2. Yearly change counts and adjustment factors.

Year number	Change count	Adjustment factor
1	538	2.7304832713754648
2	1419	1.0352360817477098
3	1469	1

The following steps were made for each change type separately. This paper uses the "new enum value added" change type to illustrate them. The historical distribution of such changes is displayed in figure 2.

After normalization, the 3-year time series containing the change count of a particular type was split into multiple 7-day time series, corresponding to how software developers usually organize their work. For each weekly time series, the mean and standard deviation of the change count were calculated because each day had a different number of changes. The received 2-D data points represent weeks with high demand for changes when the mean is high and low demand when it is low. The standard deviation indicates whether the demand is stable within the same week.

The next step was grouping the weeks the data points represent into several clusters. Each cluster must contain weeks with similar demand patterns for web API changes, leading to similar work efforts for the weeks within the same cluster. The Agglomerative Clustering method was

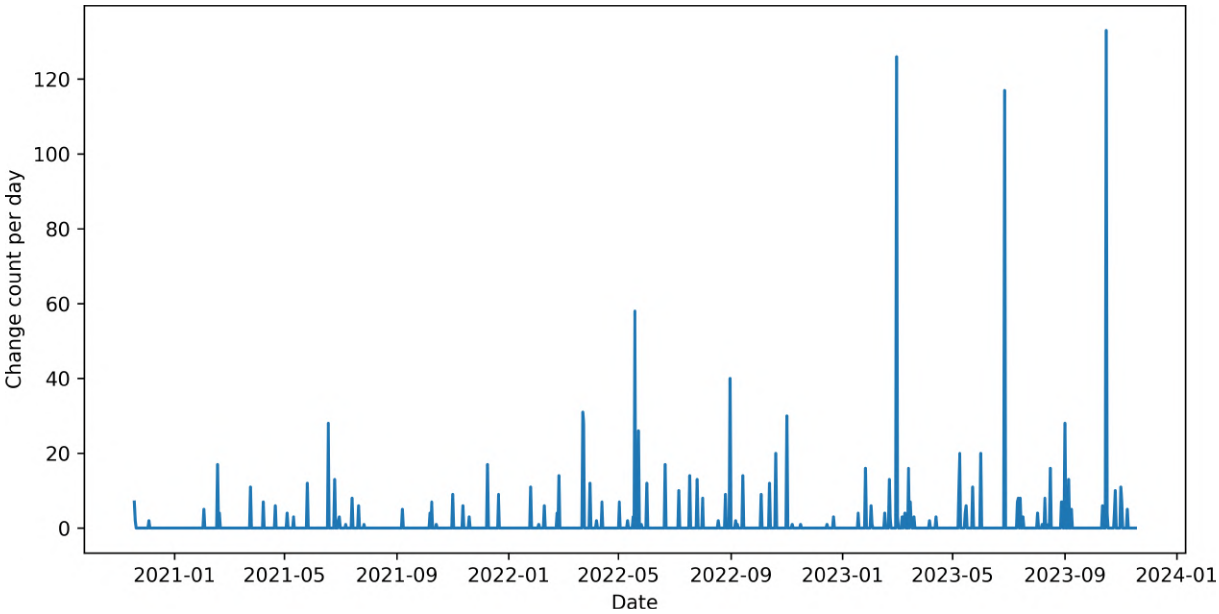

Figure 2. Historical changes of adding new enum values.

used for clustering because it is particularly effective in identifying small clusters and can handle non-spherical shapes better than K-means. The Ward linkage method, which minimizes the total within-cluster variance, was chosen because it tends to create clusters of roughly equal size and works well with quantitative features, like change count, as it uses Euclidean distance. The number of clusters selected was four for all the change types after experimenting with different numbers and visual comparison of the results. For each cluster, a centroid was calculated as the mean of all the data points belonging to the cluster, and a representative data point was found as the one closest to the centroid. Figure 3 illustrates the whole clustering process described above.

The next step was building a forecast of the change number for the next quarter. Since a representative week for each cluster was known, as well as the size of the cluster, a forecast was built by adding representative weeks proportionally to the cluster size, i.e., the number of weeks in the cluster. If the weeks of some kind were rare in the past, their representative had to be rare in the forecast, and vice versa. Keeping the right proportion was achieved with a greedy algorithm. The most underrepresented cluster was selected on each step, and the corresponding representative week was added to the forecast time series until the time series covered the whole quarter. Figure 4 shows a representative graph of the forecasted number of new enum values added and the mean and standard deviation within each week.

After constructing forecasts for each type of change, a representative forecast of the total work effort was built based on the assumption that demand for a change of a particular type requires an effort estimated for that change type. The effort was calculated separately for each day. First, the effort for each change type was calculated by multiplying the predicted number of changes and the estimated effort shown in table 1. Second, the total effort for the day was obtained by adding up the estimates for all the types of changes. Figure 5 presents the resulting representative graph.

The steps above allow for building a representative model for Stripe API that can be used to forecast the work effort necessary to support Stripe API evolution for a quarter. In the same way, a representative model can be built for any web API and any future period, given that an API changelog is available. The proposed method involves collecting and classifying

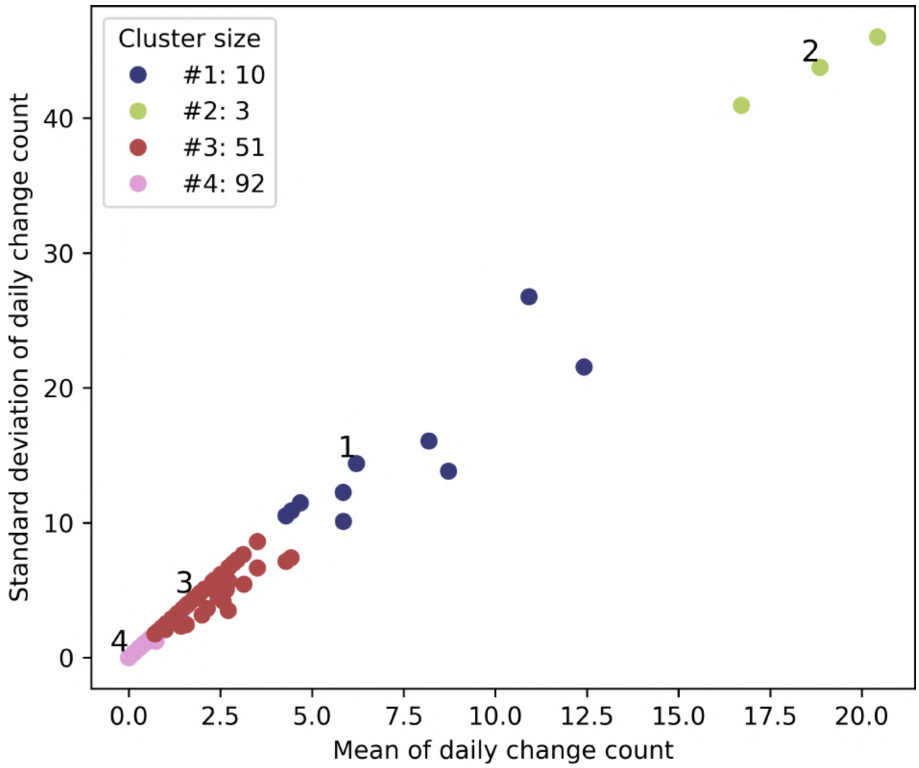

Figure 3. Clusters of similar weeks.

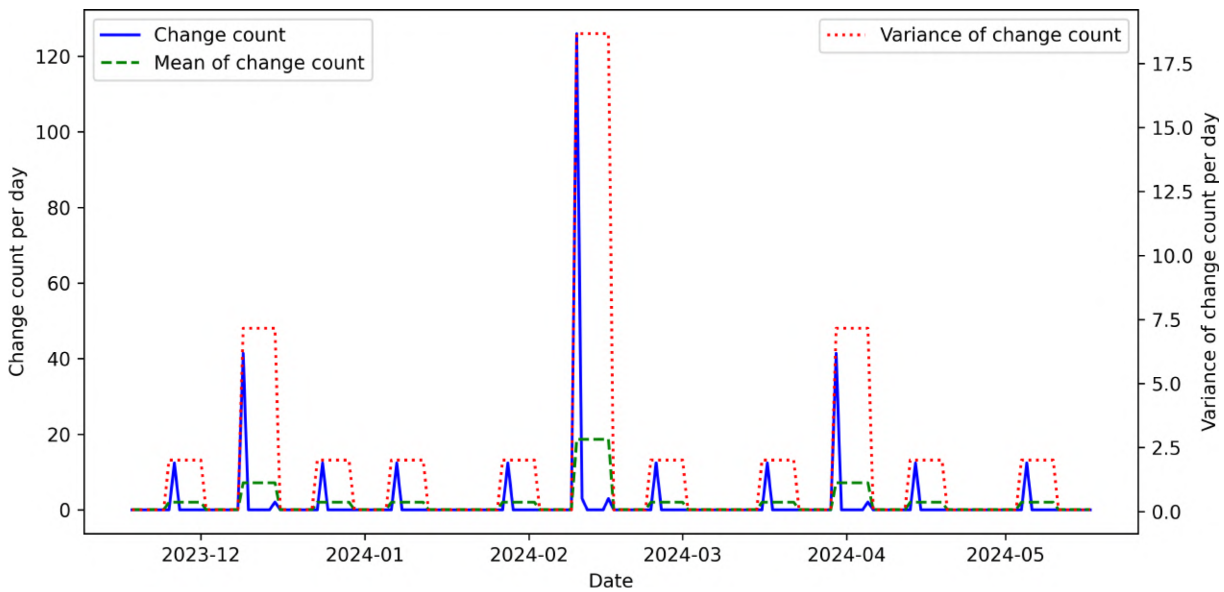

Figure 4. Forecast of adding new enum values.

API changes, estimating the effort for each change type, normalizing the data, and employing clustering to identify patterns in time series. Change demand forecasts are then constructed using a greedy algorithm for each change type, focusing on maintaining the proportion of weeks that follow different demand patterns. Finally, the change demands forecasts are combined to produce a work effort forecast.

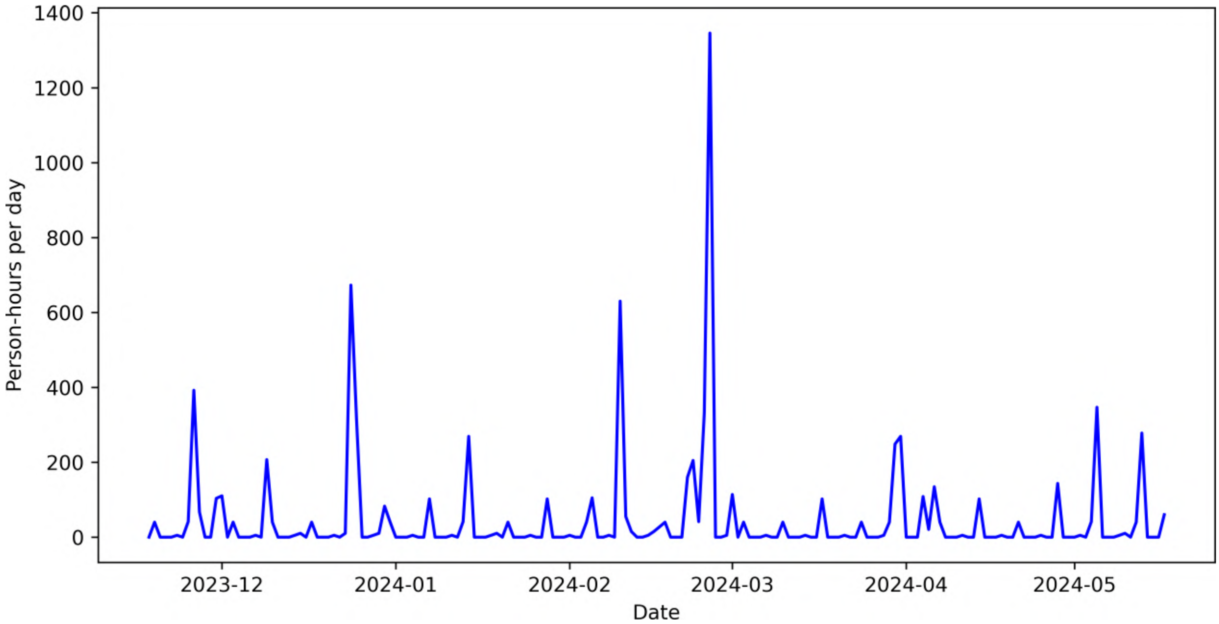

Figure 5. Forecast of work effort.

6. Conclusions

This study introduces a forecasting method designed to predict the work effort required in software development to facilitate the evolution of web APIs. The approach involves constructing a representative model that depicts the anticipated workload over a significant period, such as a quarter or a year. Cluster analysis is utilized to identify common workload patterns from historical data. The method addresses the challenge of staff planning for organizations involved in building and supporting web APIs. Future research aims to enhance forecasting precision by incorporating machine learning techniques, such as the Random Forest ensemble learning method and Multilayer Perceptron artificial neural networks.

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Modeling of cone crusher steady-state operation modes

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Modeling of cone crusher steady-state operation modes

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Abstract. The design of complex technological processes control systems involves several stages. One of the first is to analyze the steady-state operation modes of the control plant. Ore crushing is one of the most critical processes in mineral processing. The quality of its control determines the level of power consumption not only at this stage of mineral processing, but also at the subsequent ones, especially the grinding processes, which are the most energy-intensive in the entire production. The size and homogeneity of crushed ore significantly affect the power consumption of the mills. Ore is crushed by cone crushers. The crushing process is characterized by a large number of parameters. Depending on the control purpose, any of them can be considered as an input, output or disturbance. As a result, a cone crusher as a control plant is a multi-input multi-output system. The relationships between inputs and outputs are very complex, so it is very important to have an adequate mathematical description of cone crusher steady-state for its quality control. In this article, it has identified second-order polynomials regression models for the dependencies between the most significant parameters for a typical cone crusher with a mantle width 2200 mm. Namely, the dependence of the crusher electric drive power on the closed-side setting and feed capacity; the percentage of the control particle size class in the product on the closed-side setting and product capacity; product capacity on the closed-side setting, lining wear on the product capacity. The least squares method was used to estimate the parameters of the regression models.

1. Introduction

Energy efficiency is currently and will continue to be a key factor in the list of factors that ensure favourable conditions for the recovery and further sustainable development of Ukraine as a whole and its individual economic sectors in particular. At the same time, mining and mineral processing plays a key role due to its high power intensity. Analysing the energy component of mining production costs by individual stages of rock processing, it can be argued that the highest share of energy consumption is accounted for by the technological processes of ore disintegration, such as crushing and grinding. Therefore, energy efficiency improvements can be achieved mainly by improving these technological operations. There are two possible ways to do this. The first is the complete re-equipment of production lines with the latest equipment with a high level of energy efficiency. The second is to improve existing equipment and automated control procedures. The last way is more economically feasible as it does not require large investment.

At the same time, it is implemented if it is possible to identify reserves for improving energy efficiency. This is usually achieved by studying the steady-state operating modes of technological equipment. From the perspective of crushing processes, energy efficiency improvement involves reducing the level of power consumption by the crusher's electric drive while maintaining the product capacity and particle size distribution of the crushed product as regulated by technological requirements, taking into account lining wear.

2. Literature review

A fairly wide range of works is devoted to the study of steady-state operation modes of cone crushers [1–31]. In them, the authors use different modelling approaches. Depending on the type of model used in the analysis, they can be classified as follows.

Most studies use a model that describes the regularities of the crushing process using the functions of selection, breakage and classification, or the so-called Whiten's model [17, 27]. It allows describing the relationship between the particle size distribution of the feed and the product of a cone crusher. Moreover, such a model can be used when the crushing chamber is considered as a continuous object [5,9], i.e. in the form of a model with concentrated parameters, and when the crushing chamber is divided into zones through which the ore moves sequentially from the feed to the exit slot, i.e. in the form of a model with distributed parameters [2, 3, 15]. For example, in [5], the product capacity of a crushing plant is optimised. The authors use the Whiten's model as a single-zone model to determine the particle size distribution of the product at different CSS. In [2], the steady-state characteristics of the Metso GP11M crusher were obtained on the basis of a multi-zone model of a cone crusher. For different CSS, the particle size distribution of the product, the total cone crusher product capacity, and the electric drive power were determined. The mathematical description was used to simulation the secondary crushing process at a real crushing plant.

Given its wide application, this model is quite generalised and versatile, but it requires sufficient computational resources, especially when used as a model with distributed parameters, as well as when the number of classes in the particle size distribution increases.

Another class of models uses the discrete element method (DEM) to describe the crushing process in detail [6–8, 14, 24, 28, 30]. These models are characterised by high accuracy, but are quite complex in algorithmic implementation and have a significant computational burden and are not suitable for use in automated control tasks. They are mostly used in the design, construction, and modernisation of cone crushers.

Empirical models describing the steady-state of the crushing process have also been used [4, 11, 18]. For example, Bengtsson and Evertsson [4] proposes an empirical steady-state model to determine the shape of the crushed product depending on the average feed size and CSS, which is used to optimize the quality of the crushing process.

I would like to highlight the work of Yamashita, Thivierge and Euzébio [29], which is devoted to an overview of the main methods of modeling and controlling cone crushers.

Based on the analysis of steady-state modes of operation, the authors of [1, 6, 12] consider the issues of studying the functioning of cone crushers in dynamics, optimization of their performance [26], as well as the construction of automated control systems [11, 21–23] for both individual crushers and technological stages of crushing. At the same time, there is an approach to crushing control that relies on measured data rather than modeling [13].

The purpose of this article is to obtain a mathematical models of a cone crusher steady-state operation modes, which can be used in the development of a control system for a technological unit to determine the reserve for increasing energy efficiency, as well as its operating point and the limits of change in the main technological parameters.

3. Results and discussion

The main purpose of a cone crusher is to reduce the lumpy material to the required size. Therefore, the main process variables that are controlled are product capacity and a particle size distribution.

During the operation of the crusher, the input variables are the feed capacity, the closed side setting (CSS) and the eccentric rotation speed. The disturbance is represented by a set of parameters that characterise the properties of the ore (percentage of the control particle size class, hardness, fracture, splittability, moisture content, presence of clay inclusions, etc.)

The crushing process, along with the main technological output variables, is also characterised by the power consumed by the unit's electric drive, the wear of the lining plates, and the amount of ore in the crusher.

Thus, there are a lot of input and output variables to control the crusher. The connection between them is shown in the functional diagram of the unit (figure 1).

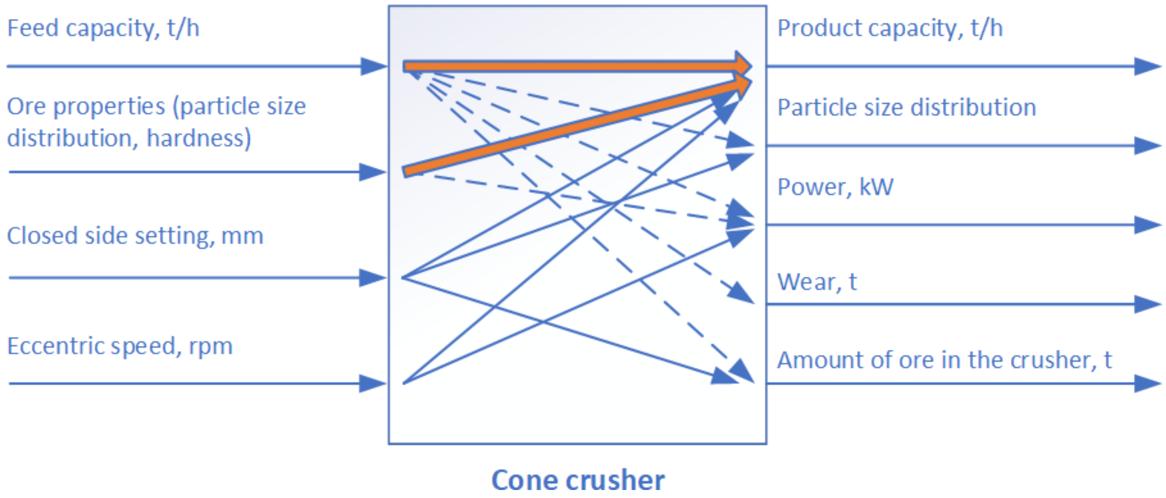

Figure 1. Cone crusher as a multidimensional control plant.

As an target of study of the steady-state properties of crushers, we choose a cone crusher with mantle width 2200 mm, which is in the final stage of crushing at the ore dressing plant No. 1 of PJSC "Pivdennyi GZK".

Let us consider in more detail the relationship between input and output variables that characterise operation modes of the crusher. Taking into account the peculiarities of the technological process at PJSC "Pivdennyi GZK" and based on the technical parameters of the cone crusher with mantle width 2200 mm and the research conducted by scientists, we will build and analyse steady-state models.

Experimental studies [32,33] have shown that at the final stages, the crushing process and the particle size distribution of the product are significantly affected by the physical and mechanical properties (hardness) of the ore. This parameter is the main disturbance. This is because the fluctuations in the cone crushers feed particle size distribution are not significant, and the feed capacity is stabilized by controlling feeders. Also, the CSS is often considered as a disturbance in steady-state modeling, for example, in [19]. It is not taken into account that this value is controllable.

The main condition for ensuring the quality of the crushing process is that crushers should not be idle or overloaded with ore. For a limited period of time, the steady-state model of the relationship between feed capacity and product capacity can be represented by the equation [34]:

$$Q_F = Q_P, \tag{1}$$

where:

Q_F is the crusher feed capacity, t/h;

Q_P is the crusher product capacity, t/h.

The cone crusher product capacity is determined by its technical parameters and ore properties.

The steady-state analysis (figure 2 a) shows that as the ore hardness increases, if the feed is constant, the crusher product capacity decreases. When higher-hardness material enters the crushing zone, the resistance to splitting increases, which leads to a decrease in the mantle rotation speed and, as a result, a sharp decrease in crusher product capacity.

Similarly, the CSS affects product capacity (figure 2 b). Increasing or decreasing the CSS leads to an increase or decrease in product capacity, respectively.

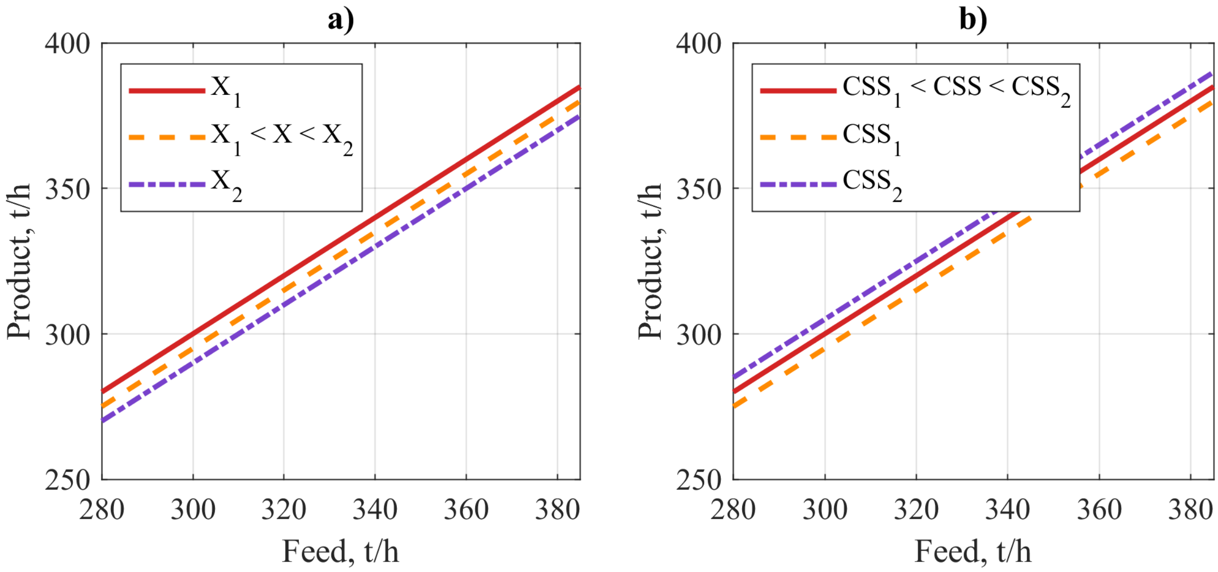

Figure 2. Crusher product capacity as a function of feed capacity: a) variable ore hardness; b) variable CSS.

In general, crusher performance is linearly related to the CSS [17, 19]:

$$\begin{gathered} Q_P\,(CSS) = Q_{P0} \pm K\Delta CSS; \\ \Delta CSS = CSS - CSS_0. \end{gathered} \tag{2}$$

where:

Q_P is the crusher product capacity at the CSS, m^3/h;

Q_{P0} is the crusher product capacity at the CSS_0, m^3/h;

K is the ratio of product capacity to the CSS, $m^3/h \cdot mm$.

Next, we will consider the crusher steady-state model of the relationship between feed capacity (Q_F) and electric drive power (P), taking into account the closed side setting (CSS). In [16], it was determined that the power consumed by the cone crusher electric drive in the operating range increases with increasing feed capacity. As a result of the simulation studies presented in [19], for crushers with a mantle diameter of 2200 mm, it was found that the power consumption has a nonlinear dependence on the crusher product capacity for different values of the closed side setting, $CSS_{\min}$, $CSS_{\min} < CSS < CSS_{\max}$ and $CSS_{\max}$ (figure 3 a). For the crusher, the closed side setting are 5 mm, 10 mm, and 15 mm, respectively.

The initial data used to build steady-state model can be approximated by second-order polynomials:

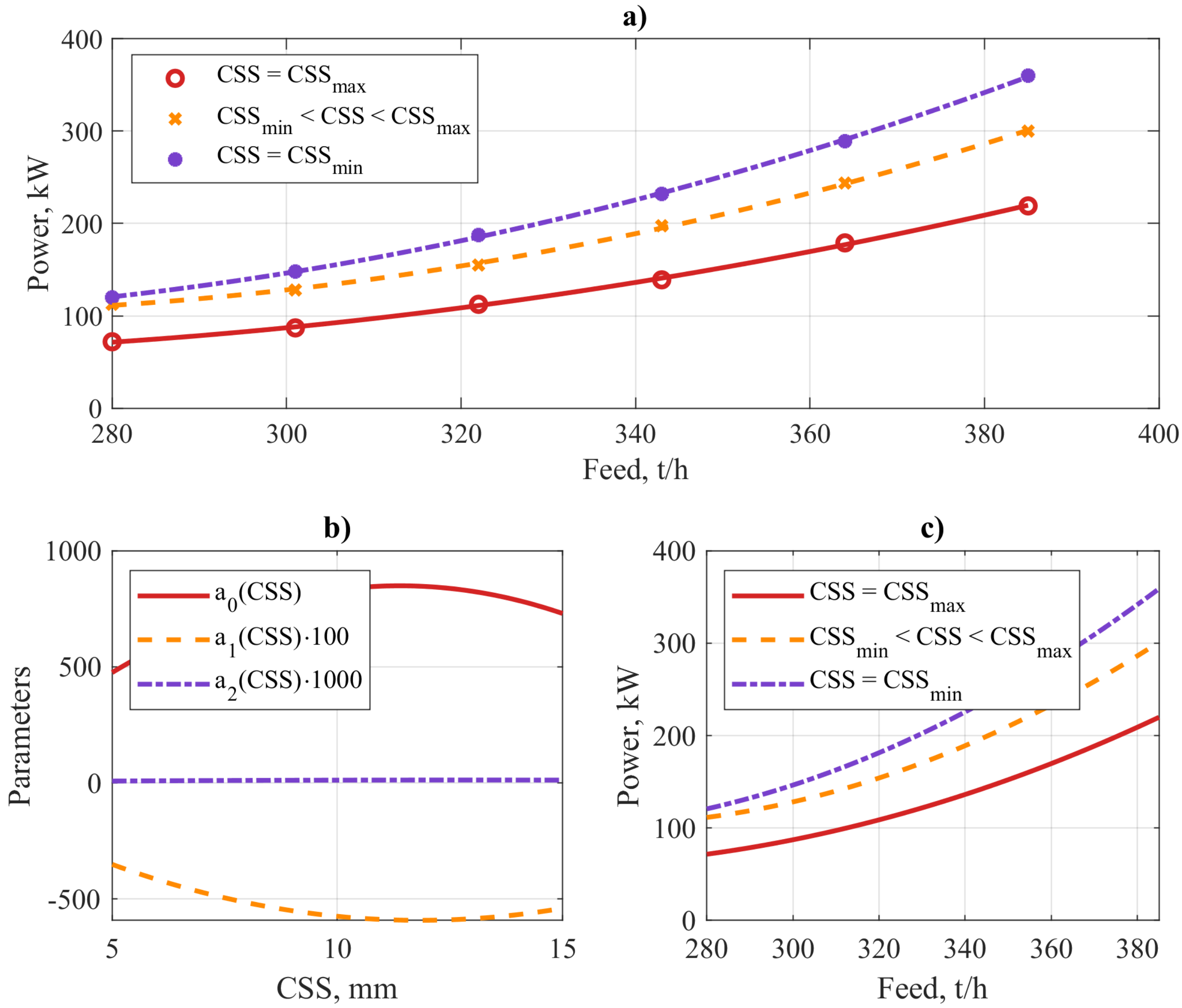

Figure 3. Electric drive power as a function of feed capacity at different values of the CSS: a) experimental data; b) polynomial coefficients; c) model data.

$$
\begin{aligned}
P_1(Q_F) &= 475.1071 - 3.5162 Q_F + 0.0074 Q_F^2; \\
P_2(Q_F) &= 831.2431 - 5.7541 Q_F + 0.0114 Q_F^2; \\
P_3(Q_F) &= 729.4167 - 5.4056 Q_F + 0.0115 Q_F^2.
\end{aligned} \tag{3}
$$

The polynomials coefficients (3) are functions of the cone crusher closed side setting. That is, they can also be approximated by the following equations:

$$
\begin{aligned}
a_0(CSS) &= -338.991071 + 208.615873 \cdot CSS - 9.159245 \cdot CSS^2; \\
a_1(CSS) &= 1.308206 - 1.223515 \cdot CSS + 0.051728 \cdot CSS^2; \\
a_2(CSS) &= -33.406 \cdot 10^{-4} + 0.001927 \cdot CSS - 75.72 \cdot 10^{-5} \cdot CSS^2.
\end{aligned} \tag{4}
$$

The result of the polynomial coefficients approximation as a function of the closed side setting is shown in figure 3 b.

Thus, the polynomial approximating the power consumed by the cone crusher electric drive as a function of two regressors – the closed side setting and the feed capacity has the following form:

$$\begin{aligned} P\left(CSS, Q_F\right) &= a_0\left(CSS\right) + a_1\left(CSS\right)\cdot Q_F + a_2\left(CSS\right)\cdot Q_F^2;\\ P\left(CSS, Q_F\right) &= -338.991071 + 208.615873\cdot CSS - 9.159246\cdot CSS^2 + \\ &+ \left(1.308206 - 1.223515\cdot CSS + 0.051728\cdot CSS^2\right)\cdot Q_F + \\ &+ \left(-33.406\cdot 10^-4 + 0.001927\cdot CSS - 75.72\cdot 10^{-5}\cdot CSS^2\right)\cdot Q_F^2. \end{aligned} \tag{5}$$

The steady-state characteristics based on equations (5) for typical CSS values (5, 10, and 15 mm) are shown in figure 3 c. At low feed capacity, the power consumption decreases with increasing closed side setting. In the case of final crushing stage at Crushing Plant No. 1 of PJSC “Pivdennyi GZK”, the feed capacity is in the range of 320 . . . 350 t/h. Thus, the required product capacity can be achieved under any expected conditions.

Lynch [19] presents steady-state model for the relationship between product capacity and percentage of particle size class +20 mm for certain closed side setting values. Data were obtained during the study of the cone crusher “Hydrocone” operating modes. This crusher has mantle width 2134 mm. Similarly, steady-state characteristics can be determined for the crusher with mantle width 2200 mm, which has similar technical parameters. The percentage of particle size class +20 mm as a function of crusher product capacity is shown in figure 4 a. With increasing product capacity, the percentage of particle size class +20 mm decreases. When the crusher product capacity is constant, the percentage of particle size class +20 mm is growing according to increasing CSS.

The initial data used to build steady-state characteristics can be approximated by second-order polynomials:

$$\begin{aligned} \gamma_1\left(Q_P\right) &= 65.0356 - 0.1827\cdot Q_P + 0.0001\cdot Q_P^2;\\ \gamma_2\left(Q_P\right) &= 82.9514 - 0.2727\cdot Q_P + 0.0002\cdot Q_P^2;\\ \gamma_3\left(Q_P\right) &= 155.5571 - 0.6635\cdot Q_P + 0.0007\cdot Q_P^2. \end{aligned} \tag{6}$$

The polynomials coefficients (6) are functions of the cone crusher closed side setting:

$$\begin{aligned} a_0\left(CSS\right) &= 104.74 - 14.23\cdot CSS + 1.18\cdot CSS^2;\\ a_1\left(CSS\right) &= -0.4167 + 0.0825\cdot CSS - 0.0066\cdot CSS^2;\\ a_2\left(CSS\right) &= 0.4146\cdot 10^{-3} - 0.1192\cdot 10^{-3}\cdot CSS + 0.0093\cdot 10^{-3}\cdot CSS^2. \end{aligned} \tag{7}$$

The result of the approximation is shown in figure 4 b.

An regression equation that approximates the percentage of particle size class +20 mm as a function of two regressors – CSS and the crusher product capacity:

$$\begin{aligned} \gamma\left(CSS, Q_P\right) &= a_0\left(CSS\right) + a_1\left(CSS\right)\cdot Q_P + a_2\left(CSS\right)\cdot Q_P^2;\\ \gamma\left(CSS, Q_P\right) &= 104.74 - 14.23\cdot CSS + 1.18\cdot CSS^2 + \\ &+ \left(-0.4167 + 0.0825\cdot CSS - 0.0066\cdot CSS^2\right)\cdot Q_P + \\ &+ \left(0.4146\cdot 10^{-3} - 0.1192\cdot 10^{-3}\cdot CSS + 0.0093\cdot 10^{-3}\cdot CSS^2\right)\cdot Q_P^2. \end{aligned} \tag{8}$$

The steady-state characteristics plotted according to equations (8) for typical CSS values (5, 10, and 15 mm) are shown in figure 4 c. The graphs show that at a low crusher capacity of 310 t/h, it is impossible to ensure the specified quality of the product. The influence of CSS

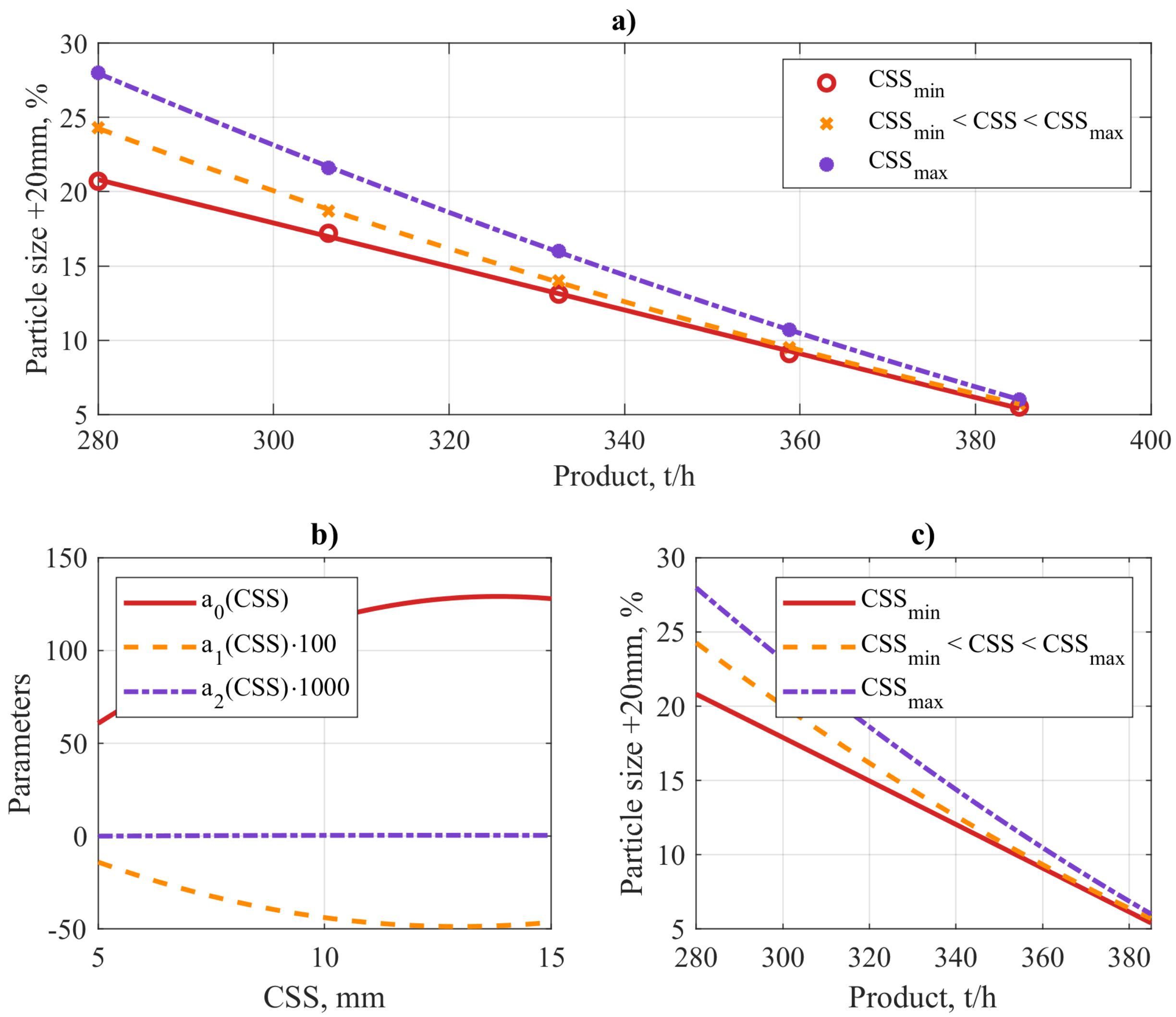

Figure 4. Dependence of the percentage of particle size class +20 mm on crusher product capacity for certain CSS: a) experimental data; b) polynomial coefficients; c) model data.

on the percentage of particle size class +20 mm is not as significant as product capacity, so adjusting CSS in the range (5 ... 10 mm) can provide an acceptable crushed ore size when the product capacity changes in the range from 320 t/h to 330 t/h. At capacity above 330 t/h, the particle size distribution can be controlled by varying the CSS in the full range (5 ... 15 mm).

During the operation of the crusher, the liners of the conecave and mantle, drive shaft bushings, eccentric contact surfaces, gears, eccentric thrust plate and other elements of the unit and electric drive wear out. The wear of the liners is essential to the product particle size distribution and power consumption. Since the liners of the conecave and mantle wears out the fastest, the steel consumption of the plates was chosen as the main parameter characterising the crusher wear.

Figure 5 a shows the steady-state characteristic obtained experimentally in [35] for the crusher with mantle diameter 2200 mm. It demonstrates the dependence of the amount of crushed ore M, thou. t over the service life of the chamber liners depending on the product capacity Q_P, t/h, on the intensity of mineral processing:

$$M\left(Q_P\right) = 3184.23 - 14.2 \cdot Q_P + 0.176 \cdot Q_P^2. \tag{9}$$

The graph shows that with increasing product capacity, the amount of crushed material increases during the period between lining replacements. Therefore, taking into account this fact and based on the data [36] that when using manganese steel lining, its consumption ranges from 0.001 to 0.005 kg per tonne of crushed ore, it can be assumed that with an increase in crusher product capacity, liner wear increases within the specified limits (figure 5 b):

$$w\left(Q_P\right) = 0.02885 - 0.2012 \cdot 10^{-3} \cdot Q_P + 0.3628 \cdot 10^{-6} \cdot Q_P^2. \tag{10}$$

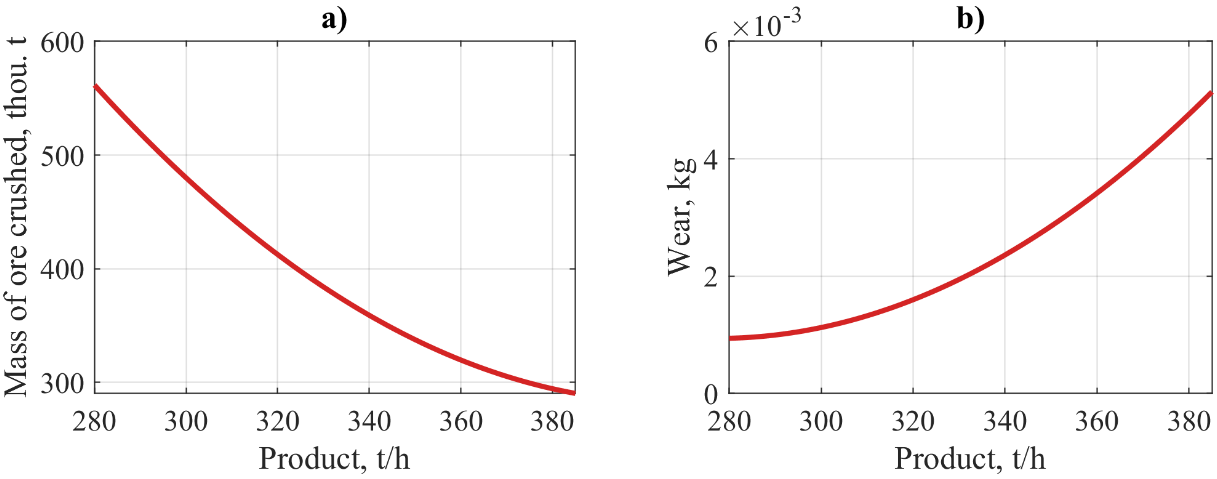

Figure 5. Steady-state wear characteristics of mantle and conecave liners.

The steady-state characteristics of liner wear are discussed in more detail in [20, 25, 31].

During industrial tests at crushing plant No. 2 of PJSC ArcelorMittal Kryvyi Rih, using the ASRi system for the Sandvik Hydrocone cone crusher, time dependencies of liner wear were obtained as shown in figure 6. The analysis of the graphs shows a low level of wear during the first 20 hours of crusher operation. Over the next 45 hours, a linear increase in wear is observed.

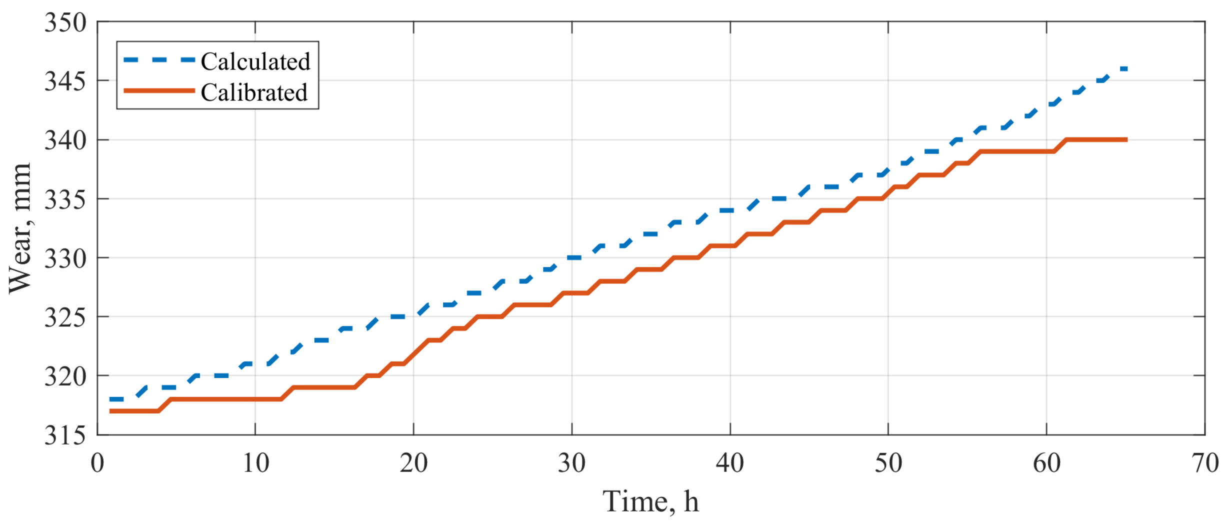

Figure 6. Timeseries of Hydrocone 7800 cone crusher liner wear: calculated and calibrated.

4. Conclusions

Proposed the mathematical description for analyzing the cone crusher steady-state operation modes. Based on experimental data from various sources, multidimensional regression dependencies are determined, which allow us to establish the regularities of the iron ore crushing process. The input variables are the feed capacity and the closed side setting. The output variables characterizing the quality of the process are product capacity, electric drive power, and the percentage of particle size class +20 mm. The model can be used to develop a cone crusher control system to determine the reserve for increasing energy efficiency, as well as its operating point and the limits for changing the main process parameters.

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Comparative analysis and modeling safe variability areas of power for VVER-1000 and AP-1000 power units

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Comparative analysis and modeling safe variability areas of power for VVER-1000 and AP-1000 power units

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Abstract. We conducted an analysis of the safe loading and power maneuvering areas for both existing VVER-1000 power units and prospective AP-1000 power units. Mathematical models were developed to represent these areas accurately. These proposed models offer a comprehensive assessment of the potential operating conditions for Nuclear Power Plant units within the context of evolving energy systems, which are increasingly reliant on renewable energy sources. By adequately accounting for the limitations and constraints associated with safe power output maneuvering, these models facilitate informed decision-making processes regarding the integration and operation of VVER-1000 and AP-1000 nuclear power units alongside wind and solar power plants in electric power systems. This ensures the safe and efficient operation of NPP units while accommodating the growing penetration of renewable energy sources in the overall energy mix.

1. Introduction

The modern development of many energy systems involves a significant increase in the share of energy production from renewable energy sources (RES), which are characterized by variable and difficult to predict energy production schedules [1–3]. A comparative analysis of the forecast residual load of the electric power system of Ukraine, conducted by the authors under the conditions of an increase in uncontrolled volumes of electricity production by the generating units of wind and solar power plants from 7% in 2021 to 30% in 2050, shows significant changes in the load schedules of controlled generating capacities. The load of the latter increases both in terms of capacity and its variability in the summer and winter seasons, respectively figure 1.

As the share of electricity production from RES gradually increases, there arises a need to explore the potential involvement of Nuclear Power Plant (NPP) units to operate in modes significantly different from the so-called basic mode, while maintaining an almost unchanged level of thermal power output. This becomes particularly relevant for energy systems with a significant proportion of electricity production coming from NPPs.

Given that NPPs in Ukraine accounted for approximately 55% of the total annual electricity production between 2015 and 2023, extensive research has been conducted on licensing the power maneuvering mode of existing VVER-1000 power units. Currently, the future development of Ukraine's energy system until 2050 is being considered under the condition of constructing new power units utilizing AP-1000 technology.

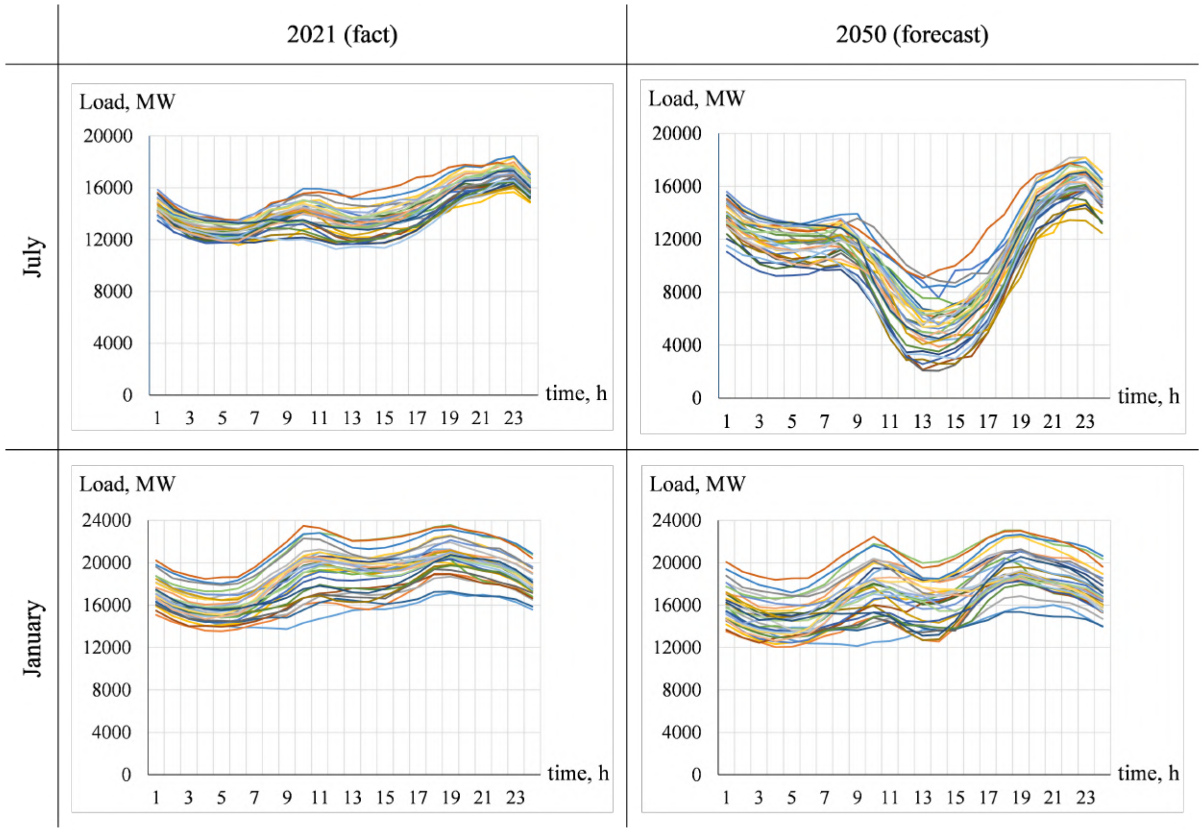


Figure 1. Residual load of Ukraine's energy system under the conditions of increasing electricity production from wind and solar power plants from 7% in 2021 to 30% in 2050, while assuming no changes in the structure of the specified production volumes. The graphs for 2021 are based on the actual data of NEC "Ukrenergo", and the graphs for 2050 correspond to the forecast calculations of the authors.

To address the challenges associated with planning the development of energy systems, it's imperative to consider the safe operation conditions of NPP units under varying thermal power regimes. This task becomes significantly more complex when dealing with energy systems that employ reactors of different types.

In order to ensure the accuracy of mathematical formulations for energy system development planning, it's essential to augment them with a formalized mathematical description of the permissible safe thermal load areas for each reactor design. This description should account for inherent limitations on thermal power levels and the rate at which they can change over time.

2. Design limitations regarding the operating modes of the VVER-1000 and AP-1000 power units

Ensuring the safe operation of NPP under varying loads is contingent upon adhering to predetermined limit values for changes in thermal power, the rate of change of thermal power, and the number of cycles of such changes during the fuel campaign, as specified in the power unit's design. These parameters are crucial for maintaining the structural integrity and operational stability of the power unit, particularly when subjected to fluctuating loads. Exceeding the permitted limit values could lead to undesirable consequences, including potential damage to equipment, decreased operational efficiency, and compromise of safety standards.

Therefore, it is imperative for nuclear power plant operators to monitor and control these parameters within the prescribed limits throughout the operational lifespan of the power unit. This entails implementing robust monitoring systems, adhering to established operational protocols, and conducting regular inspections and maintenance activities to ensure compliance with safety regulations and mitigate operational risks.

According to the "Standard technological regulations for the safe operation of NPP power units with VVER-1000 reactors" RG-B.0.03.179-13, increasing the power of the reactor to the nominal level should be carried out in automatic mode. Increasing the power of the reactor should be carried out while ensuring that the restrictions on the conditions for ensuring the integrity of the nuclear fuel are not exceeded and that the limit changes of the relevant technological parameters are not exceeded. The project stipulates that for VVER-1000 the rate of increase in thermal power of the reactor should not exceed $0.01n_0$ per minute, where n_0 is installed capacity of the reactor. In addition, with significant fluctuations in power, the design requirements for safe operation of the reactor provide for holding for three hours at a power level of $(0.75 - 0.85)n_0$ to ensure relaxation processes in the nuclear fuel and stabilize the fluctuations of the energy release field in the active zone. In the case of a decrease in the thermal power of the reactor, safety conditions can be ensured at a rate of change of power of no more than $0.03n_0$ without other restrictions.

The analysis of the possibility of operation of the NPP power unit in daily power regulation is given in [4], taking into account the classic schedule of changes in thermal power according to the algorithm $(1.0 - 0.75 - 1.0)n_0$ with operation at nominal power for $12 - 18$ hours and at a reduced level capacity for $6 - 12$ hours. At the same time, it is shown the possibility of ensuring safe operating conditions of nuclear fuel and not exceeding the technical limitations established in the reactor design, which allows maneuvering the power of the NPP power unit in a wide, but limited from below, range of changes in its thermal power. Practical confirmation of the possibility of operation of a high-power reactor in a fixed algorithm of changing its load was carried out in 2015 at power unit No. 2 of the Khmelnytsky NPP. According to the results of the experimental operation of the daily power regulation mode, there were no changes in the specific activity of the coolant of the first circuit exceeding the permissible range, violations of the limits and operating conditions established by the technological regulations for the safe operation of the VVER-1000 power unit. The total number of reactor load changes foreseen by the rigid schedule is 200 for the fuel company and 800 for the period of operation of the nuclear fuel in the reactor core. The possibility of operating the reactor in the mode of daily power regulation is confirmed for no more than 2/3 of the fuel campaign.

The power change parameters of the VVER-1000 provided in the technological regulations are justified in the project and regulated, based on the requirements of safe operation of the reactor under the conditions of operation of the power unit in the basic mode at an almost constant level of thermal power. At the same time, the design of the VVER-1000 reactor provides for a list of modes that are currently not used in the operation of NPP power units and are not included in the list of permitted modes in the technological regulations for safe operation, but can potentially be considered acceptable for implementation under the conditions of experimental confirmation. The operation of the reactor under conditions of variable power can be studied for the following load modes:

- Operation of the power unit in the range of thermal power change of $(0.3 - 1.0)n_0$ without limiting the time spent at any power level and power change after long-term operation of the power unit in this range at the permitted speed;
- Daily reduction of power unit capacity to the level of own needs or to the state of "hot stop" for 5-8 hours and further increase of capacity at the permitted speed;
- Reduction of power to the level of own needs or to the state of "hot stop" on non-working days for a period of 24-25 hours and further increase of power at the permitted speed.

But currently, in accordance with the requirements of ensuring the stability of the energy system, the classic algorithm of daily regulation with the power of VVER-1000 in the range of $(1.0 - 0.8)n_0$ is actually being considered. Further development of reactor technologies takes place based on the need to ensure economical and safe operation of power units in conditions of flexibility of energy systems. Based on the analysis conducted, the AP-1000 reactor of the Westinghouse company is considered in Ukraine as the most modern example of the implementation of appropriate technological solutions for electricity generation using nuclear power plants.

AP-1000 is a water-water power reactor with extensive use of safety systems based on the passive principle of action. The operator's influence on reactor control during normal operation and accidents is minimized. AP-1000 allows you to work in the mode of monitoring the load in the power system. When the frequency changes in the power system, the reactor power is automatically increased and vice versa. According to [5], the operation of the power unit in the mode of daily power regulation is ensured for 90% of the duration of the fuel campaign. At the same time, the change in reactor power occurs only due to the use of absorbers in the form of rods without the use of a boron regulation system to reduce neutrons in the active zone, which leads to the minimization of the accumulation of radioactive waste and an increase in the efficiency of operation of the power unit. The logic of the construction of the control system ensures compliance with safety requirements during transient processes in the reactor without reaching the settings of the protection system.

The system of influencing the parameters of the active zone provides for the possibility of changing the thermal power of the reactor and controlling the distribution of thermal power in the reactor itself. The design of the AP-1000 reactor allows for a gradual (sudden) change in thermal power in the range of $\pm 0.1n_0$ without affecting the parameters of fuel and main equipment in a wide range of power regulation:

- From n_0 to $0.25n_0$ when power is reduced;
- From $0.15n_0$ to $0.9n_0$ when increasing the power of the reactor.

Separately, the conditions of safe operation of the power unit are confirmed for deep changes in reactor power up to $0.2n_0$ from the current level at a rate of change of power of no more than $0.02n_0$/min.

The operation of the power unit in the daily power regulation is based on the following algorithm:

- Power reduction from n_0 to $0.5n_0$ for 2 hours;
- Operation at a reduced power level in the range of $(1.0 - 0.5)n_0$ from 2 to 10 hours;
- Power increase to n_0 for 2 hours with further work at the nominal power level;
- Rate of power change up to $0.05n_0$/min.

According to [6], a comparative analysis of AP-1000 and VVER-1000 shows a more flexible algorithm of AP-1000 operation in daily power regulation, which can be described by the scheme (18-2-2-2) instead of (12-3-6-3) for the VVER-1000 during 90% of the fuel campaign and the actual absence of restrictions on the need to ensure the dwell time over the entire range of reactor power changes. Comparison of design characteristics of VVER-1000 and AP-1000 power units are presented in 1.

The analysis of the suitability of the VVER-1000 operation under the conditions of design restrictions regarding the change in the thermal power of the reactor to support the stability of the flexible energy system with a significant presence of renewable energy sources was performed in [1]. Two operating modes of the power unit in daytime supply of peak loads "12-3-6-3" and "15-1-7-1" were considered using the example of high-power AP-1000 power units. For both cases, the power unit unloading depth did not exceed $0.3n_0$. It is shown that the operation of

Table 1. Comparison of design characteristics of VVER-1000 and AP-1000 power units.

	VVER-1000	AP-1000
The range of thermal power change	$(1.0 - 0.5 - 1.0)n_0$	$(1.0 - 0.15 - 1.0)n_0$
The rate of reduction of thermal power	$R_- = 0.03n_0/\text{min}$	$R_- = 0.05n_0/\text{min}$
The rate of increase in thermal power	$R_+ = 0.01n_0/\text{min}$	$R_+ = 0.05n_0/\text{min}$
Exposure time at 80% power level	3 hours	Without limits
The permissible range of sudden changes in thermal power	–	$0.1n_0$

the nuclear power plant in a variable load leads to an increase in the flexibility of the power system in comparison with operation at the nominal power level. It was concluded that the "15-1-7-1" scheme better meets the conditions of variability due to the increase in the rate of change of power of the NPP power unit.

Further analysis of the adequacy of the classic algorithm of NPP operation to ensure the daily balance of electricity was performed in [2]. In addition to [1], the scenario of the optimal operation scheme of the power unit based on the conditions of the power system is considered. It is shown that unlike the algorithm of NPP operation with fixed restrictions on depth and unloading/loading rates, the optimized algorithm can properly organize the sequence of regulation of peak load and power of all units and significantly reduce operating costs, which improves the economy of power system dispatching.

3. Mathematical description of safe region maneuvering the thermal power of the nuclear power plant reactor

Let the function $f(N)$ be defined, representing the dependence of the maximum permissible rate dN/dt of increase in the relative thermal power of the power unit reactor on its current value $N = n/n_0$. Typically, the function $f(N)$ is a piecewise smooth function with I smoothness intervals $\{N_i, i \in I\}$. This function can be represented by the sum of smooth functions $f_i(N)$, denoted as

$$f(N) = \sum_{i \in \mathcal{I}} f_i(N) \mathbf{1}_i(N), \tag{1}$$

where for $\forall i \in \ I$, the function $\mathbf{1}_i(N)$ takes a specific form

$$\mathbf{1}_i(N) = \begin{cases} 1, & N \in N_i \\ 0, & N \notin N_i \end{cases}.$$

Referring to the definition

$$\frac{dN}{dt} = f(N),$$

we obtain a differential equation with separated variables N and t in the form

$$\frac{1}{f(N)} dN = dt$$

or in the equivalent integral form

$$\int\limits_{N}^{N+\Delta N} \frac{1}{f(x)} dx = \int\limits_{t}^{t+\Delta t} dy. \tag{2}$$

The integration is performed over the time interval $(t, t+\Delta T)$ with a duration of ΔT. During this interval, the relative thermal power of the power unit reactor increases at the maximum permissible speed from the initial value of N to the final value of $N + \Delta N$.

Considering expression (1), we express integral equation (2) in the following form:

$$\int_{N}^{N+\Delta N} \sum_{i\in\mathcal{I}} \frac{1}{f_i(x)} \mathbf{1}_i(x)dx = \Delta T. \tag{3}$$

For $\forall i \in I$, suppose that the smooth functions of $1/f_i(x)$ correspond to the original functions of $F_i(x)$. Then, the integral equation (3) can be expressed as the following algebraic equation

$$\sum_{i\in\mathcal{I}} F_i(N+\Delta N)\mathbf{1}_i(N+\Delta N) \;\; - - \sum_{i\in\mathcal{I}} F_i(N)\mathbf{1}_i(N) = \Delta T, \tag{4}$$

and solving it enables the establishment of the dependence of $\Delta N = \Delta N(N, \Delta T)$.

Referring to table 1, for the VVER-1000, we have the value of the upper limit of the rate of increase of its relative thermal power in 1 minute in the form of a set of functions presented in table 2.

Table 2. Functional dependencies of the rate of increase in the relative thermal power of the VVER-1000 power unit reactor on the value of such power.

Smooth function $f_i(N)$	Original function $F_i(N)$ for $f_i^{-1}(N)$	Definition interval $N_i, N \in N_i$
$f_1(N) = 0.01$	$F_1(N) = N/0.01$	$N_1 = (0.50, 0.75)$
$f_2(N) = 1/1800$	$F_2(N) = 1800N$	$N_2 = (0.75, 0.85)$
$f_3(N) = 0.01$	$F_3(N) = N/0.01$	$N_3 = (0.85, 1.00)$

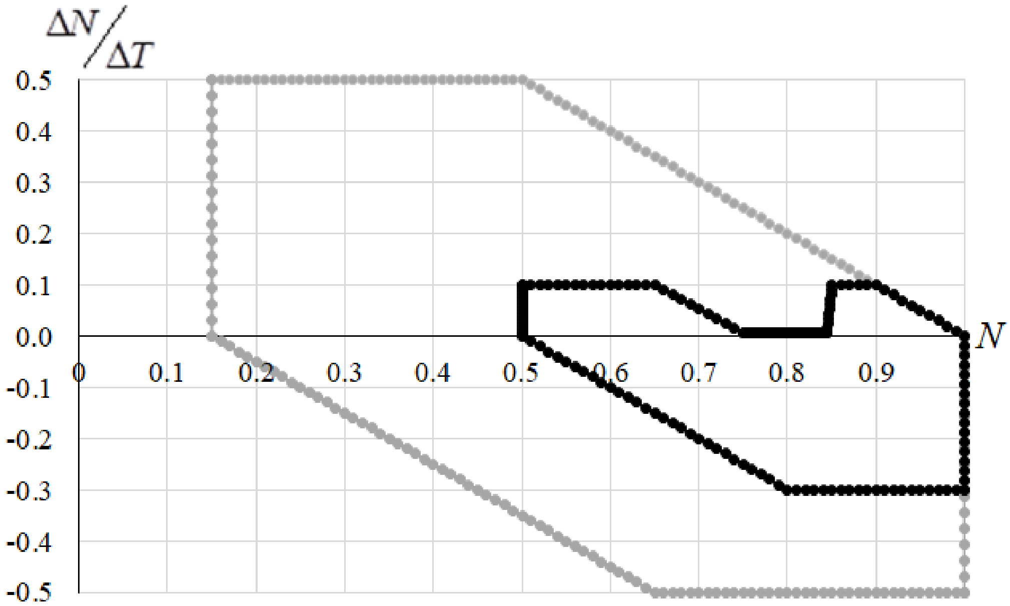
4. Safe regions for maneuvering the thermal power of the VVER-1000 and AP-1000 reactors

Solving equation (4) with respect to ΔN for various values of N and within fixed time intervals ΔT, namely 10 minutes and 1 hour, yields characteristic depicting the maximum rate of increase in thermal power of the VVER-1000 and AP-1000 power unit reactors from its current value. These characteristics are presented in figure 2. The characteristics obtained reflect the power unit's capabilities to operate safely during maneuvering modes.

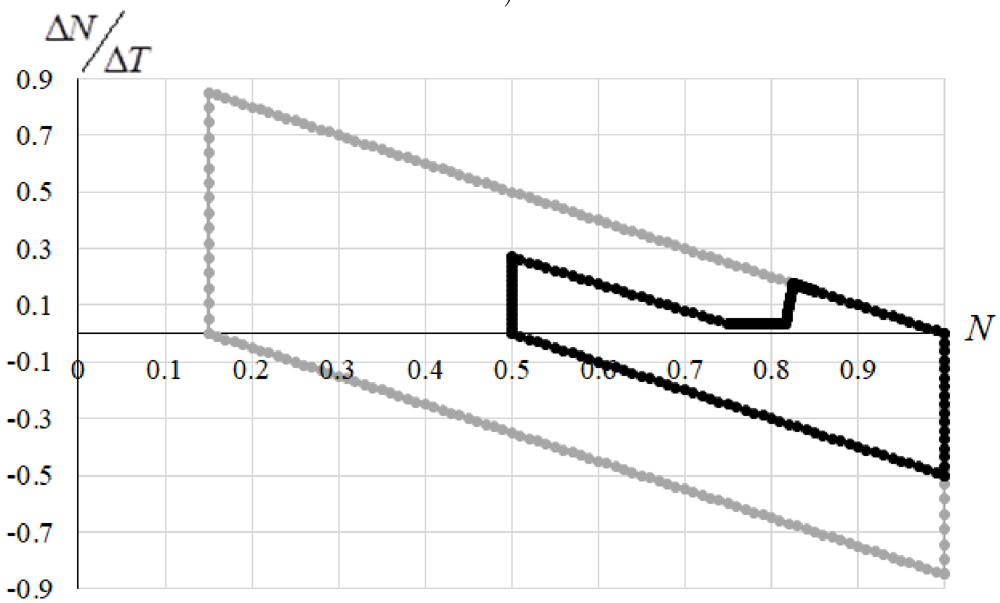
From the characteristics defined, it follows that the reactor units of the VVER-1000 have the largest value of the installed capacity utilization factor in modes close to the nominal load, where power maneuvering is limited enough to increase. Meanwhile the safe load follow operation is technically possible within wider limits of lower thermal power level (less than $0.7n_0$) with low efficiency of the power unit. Furthermore, the transition from the low-load region to loads approaching nominal values is notably extended, necessitating a minimum three-hour residence in load modes $(0.75 - 0.85)n_0$, where maneuvers to increase power are almost impossible.

Instead, the areas of safe maneuvering with the power of the AP-1000 power unit are much wider in a comparatively larger range of its loads.

It is essential to incorporate these conditions of safe loading and power maneuvering for the VVER-1000 and AP-1000 power units into dispatching models of electric power systems and planning tasks for their development.



a)



b)

Figure 2. Safe regions for maneuvering the thermal power of the VVER-1000 (outlined by a black line) and AP-1000 (outlined by a gray line) reactors within ΔT equal 10 minutes (a) and 1 hour (b).

In unit commitment and economic dispatch models [1, 7–9], the value p_t of the load of the generating unit AP-1000 at the current time t depends on the value $p_{t-\Delta T}$ of its load at the previous time $t - \Delta T$ and satisfies the following system of restrictions

$$\begin{cases} 0.15n_0 \le p_t \le n_0 \\ p_t - p_{t-\Delta T} \le R_+\Delta T \\ p_{t-\Delta T} - p_t \le R_-\Delta T \end{cases} . \tag{5}$$

The mathematical description of the area of safe maneuvering by the power of the VVER-1000 power unit is more complex. The upper limit of the rate of increase in power is a piecewise linear function depending on the parameter ΔT. For a fixed value of parameter ΔT, this function has the form

$$\Delta N_a(N,\Delta T) = \sum_{i\in I_a}(\alpha_i + \beta_i N)\mathbf{1}_{ai}(N,\Delta T). \tag{6}$$

The function $\Delta N_a(N,\Delta T)$ is defined on the set $I_a = I_a(\Delta T)$ of linear functions $\{\alpha_i + \beta_i N,\ i \in I_a\}$ with coefficients $\alpha_i = \alpha_i(\Delta T)$ and $\beta_i = \beta_i(\Delta T)$. The unit functions $\{\mathbf{1}_{ai}(N,\Delta T),\ i \in I_a\}$ defined on the intervals $\left\{\underline{N}_i < N < \overline{N}_i,\ i \in I_a\right\}$ (table 3). Using the binary function $u_{i,t}$ and taking expression (6) into account, we obtain the following description of the area of safe maneuvering by the power of the VVER-1000 power unit:

$$\begin{cases} 0.5n_0 \le p_t \le n_0 \\ p_{t-\Delta T} \le n_0 \sum\limits_{i\in I_a} u_{it}\overline{N}_i \\ p_{t-\Delta T} \ge n_0 \sum\limits_{i\in I_a} u_{it}\underline{N}_i \\ \sum\limits_{i\in I_a} u_{it} = 1 \\ 0.15n_0 \le p_t \le n_0 \\ p_t - p_{t-\Delta T} \le n_0 \sum\limits_{i\in I_a} u_{it}(\alpha_i + \beta_i p_t/n_0) \\ p_{t-\Delta T} - p_t \le R_-\Delta T \end{cases}. \tag{7}$$

Table 3. Coefficients of linear functions $\{\alpha_i + \beta_i N,\ i \in I_a\}$ and limits of their definition intervals $\left\{\underline{N}_i < N < \overline{N}_i,\ i \in I_a\right\}$.

$\Delta T = 10$ min

$i \in I_a$	α_i	β_i	$\underline{N}_i$	$\overline{N}_i$
1	0.100000	0.000000	0.500000	0.650000
2	0.713889	-0.944444	0.650000	0.750000
3	0.005556	0.000000	0.750000	0.844444
4	-5.121428	6.071429	0.844444	0.860000
5	0.100000	0.000000	0.860000	0.900000
6	1.000000	-1.000000	0.900000	1.000000

$\Delta T = 1$ hour

$i \in I_a$	α_i	β_i	$\underline{N}_i$	$\overline{N}_i$
1	0.741667	-0.944444	0.500000	0.750000
2	0.033333	0.000000	0.750000	0.816667
3	-13.850000	17.000000	0.816667	0.825000
4	1.000000	-1.000000	0.825000	1.000000

The resulting systems of constraints (5) and (7) serve as mathematical models representing safe maneuvering areas for AP-1000 and VVER-1000 power units. These models are specifically designed to accurately capture the characteristics of safe maneuvering regarding the power output of both existing and promising NPP units. They are intended to be utilized in tasks related to planning the development of electric power systems with significant shares of electricity production generated by wind and solar power plants.

These mathematical models provide a framework for assessing and ensuring the safe operation of NPP power units within the context of evolving energy systems characterized by a growing reliance on renewable energy sources. By adequately reflecting the constraints and limitations associated with safe maneuvering of power output, these models contribute to informed decision-making processes regarding the integration and operation of NPP units alongside wind and solar power plants within electric power systems.

5. Conclusion

The operation of electric power systems with a significant proportion of renewable energy sources imposes stringent requirements on the operational conditions of both existing and new Nuclear Power Plant (NPP) units. The ability of a power unit to operate in modes involving daily power regulation with deep unloading, while still meeting other safety requirements, becomes a critical factor when selecting reactor technology for the prospective construction of new nuclear power plants.

The technological solutions employed in the design of the AP-1000 power unit render this reactor technology highly promising in addressing these operational requirements. The presented mathematical models outlining safe power maneuvering areas for both VVER-1000 and AP-1000 reactors ensure the adequacy of their representation in tasks involving the evaluation of economic efficiency. These models are crucial in making decisions regarding the commissioning and operation of reactors of this type within the framework of planning the development of generating capacities for electric power systems.

In summary, the capability of NPP units to operate safely and efficiently in modes involving daily power regulation with deep unloading is a significant consideration in the context of power system operation with a high proportion of renewable energy sources. The technological advancements and mathematical modeling techniques associated with reactors like the AP-1000, VVER-1000, and others play a vital role in ensuring the reliability and sustainability of nuclear power as part of the overall energy mix in the evolving landscape of electric power systems.

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Comprehensive approach to calculating operational parameters in hydraulic fracturing

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Comprehensive approach to calculating operational parameters in hydraulic fracturing

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Abstract. Hydraulic fracturing (HF) stands as a pivotal method in the development of challenging hydrocarbon reserves, particularly those associated with low-permeability and fractured reservoirs. As these reserves constitute approximately one-third of global hydrocarbon resources, HF has emerged as an indispensable technology for their extraction. The creation of high-conductivity fractures through HF has demonstrated a remarkable capacity to amplify well flow rates, often achieving two to threefold or greater increases. This study seeks to establish robust scientific and methodological foundations for the calculation of operational parameters in HF by synthesizing insights from theoretical research. Emphasizing a comprehensive design approach, the methodology underscores the pivotal role of dynamic parameters such as fluid type, proppant characteristics, and injection rate in optimizing the efficiency of HF operations. To enhance efficiency, an automated algorithm is proposed for the judicious selection of proppants, facilitating expedited calculations and optimization processes. The proposed approach not only streamlines the parameter selection process but also ensures the implementation of the most effective HF scenarios. Additionally, it serves as a foundational framework for the development of automated tools for HF calculations in field applications, thereby advancing the field of hydrocarbon reservoir development.

1. Introduction

Currently, hard-to-recover hydrocarbon reserves confined to low-permeability, poorly drained, heterogeneous, and dissected reservoirs are widely involved in development. Hydraulic fracturing (HF) is one of the most effective methods for increasing the productivity of injection, oil and gas wells that penetrate such formations. Currently, about a third of hydrocarbon reserves can only be recovered using this technology. Highly conductive hydraulic fracturing cracks make it possible to increase well production by 2–3 times or more.

The essence of hydraulic fracturing is the injection of fluid under pressure, which fills microcracks and “weeds” them, and forms new cracks. If you introduce a fixing material (for example, sand) into the formed or widened cracks, then after the pressure is removed the cracks do not close. As a result, the conductivity of the productive formation increases, which leads to the intensification of hydrocarbon production [1, 2].

The highest efficiency of hydraulic fracturing is achieved with an integrated design approach based on factors such as formation conductivity, fracture mechanics, fracturing fluid and proppant characteristics. To implement this approach, in addition to models of fracture formation, it is necessary to create models of filtration in a system of wells with hydraulic fractures and study the characteristics of fluid flow in the vicinity of a fracture, including in heterogeneous and water-logged formations. Therefore, it seems relevant to develop methods for mathematical modeling of hydrodynamic processes in the development of oil and gas fields using hydraulic fracturing based on theoretical research and modern computer technologies.

The purpose of the work is to propose a scientific and methodological basis for calculating the operating parameters of hydraulic fracturing based on generalizing the results of theoretical studies and assessing the technological efficiency of hydraulic fracturing [3, 4].

2. Key parameters in hydraulic fracturing optimization

When hydraulic fracturing is carried out in the near-wellbore zone, cracks of various spatial orientations can form horizontal, vertical, or inclined (figure 1) [5]. To determine the geometry of the created crack, it is necessary to evaluate the mechanical properties of rocks, such as stress, Young's modulus, Poisson's ratio, as well as external parameters: injection rate, pressure, and others.

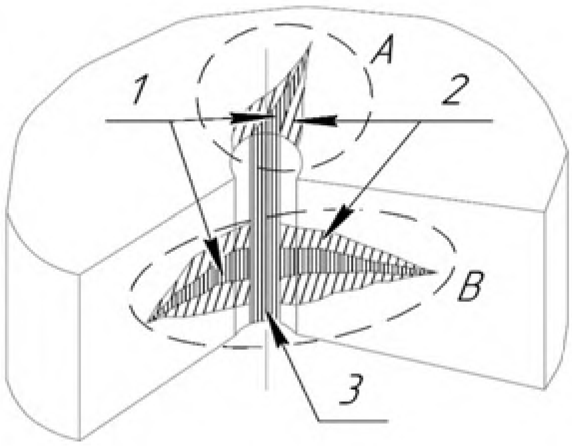

Figure 1. Vertical crack diagram: A – vertical crack; B – horizontal crack; 1 – crack zone; 2 – infiltration zone; 3 – well.

If a filtering fluid is injected into the bottom-hole zone of a well, then filtration begins in the most permeable areas, determined, as a rule, by the presence of cracks. Filtration is possible only at a certain pressure drop: ΔP_f, depending on the pressure difference in the well P_w and the formation P_l [6]:

$$\Delta P_f = P_W - P_l. \tag{1}$$

In this case, the poorly filtered liquid acts as a wedge, increasing the length and opening of the horizontal crack. In this case, a positive result can be obtained only at a certain rate of injection of fracturing fluid. The minimum injection rate of fracturing fluid is determined by the empirical relationship [7]:

$$Q_{min.g} \geqslant 10^6 \frac{\pi R_g \omega_o}{\mu}, \tag{2}$$

where $Q_{min.g}$ is the minimum supply of fracturing fluid by the pumping unit for the formation of a horizontal crack, m^3/s; R_g is the radius of horizontal crack, m; ω_o is the crack width on the well wall, m; μ is the viscosity of the fracturing fluid, mPa·s.

In principle, the formation of a horizontal crack and filtered liquid is possible, which is associated with a significant increase in the rate and pressure of injection.

If a non-filtering fracturing fluid is used, the stress in the rock increases as injection pressure increases. At a certain stress that exceeds the compressive strength of the rock, the rock breaks. Physically, this process proceeds as follows. As the injection pressure increases, the stress in the rock increases and compression occurs. Compression occurs to a certain limit, determined by the compressive strength. Once this limit is exceeded, the rock cannot resist increasing compression and cracks. After the injection pressure is removed, residual cracks (decompaction cracks) appear, usually with a vertical or inclined orientation [8].

The minimum injection rate of fracturing fluid is calculated using the following empirical relationship [9]:

$$Q_{min.v} \geqslant 10^6 \frac{h\omega_o}{\mu}, \tag{3}$$

where $Q_{min.v}$ is the minimum supply of fracturing fluid by the pumping unit for the formation of a vertical crack, m^3/s; h is the formation thickness, m.

Since during the injection process a certain part of the fluid is filtered into the rock ΔQ_f, forming an infiltrate zone along the fractures, the actual rate of injection of the fracturing fluid Q_d must be higher than that calculated using formulas (2) and (3) [10]:

$$Q_d = Q_{min} + \Delta Q_f. \tag{4}$$

On figure 2 the dependence of the hydraulic fracture half-length on the Young's modulus of the rock is shown for different hydraulic fracturing fluid efficiency. Similar graphs for crack height Hydraulic fracturing are presented on figure 3 [11].

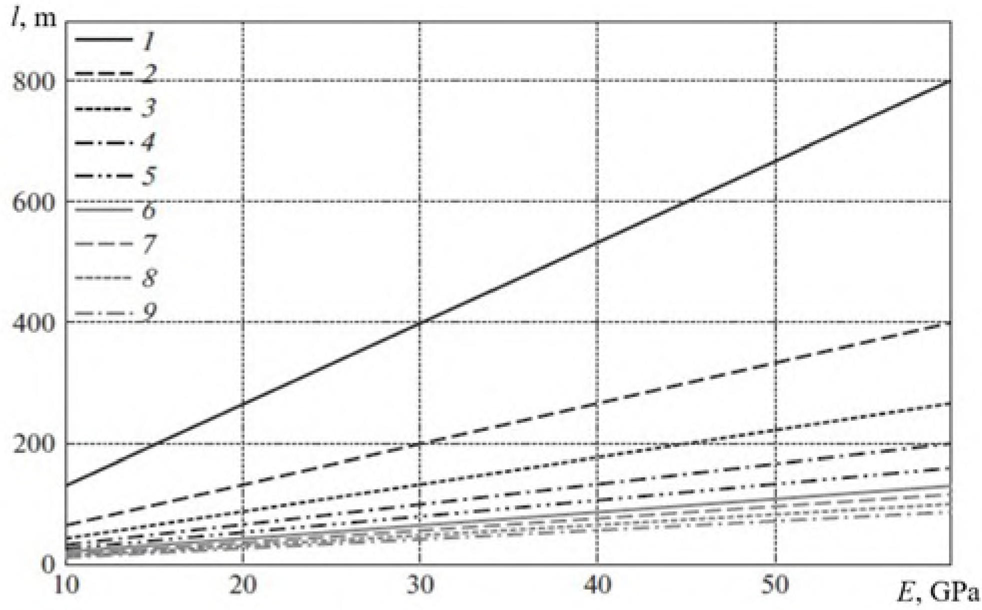

Figure 2. Dependence of the fracture half-length on the Young's modulus of the rock for different hydraulic fracturing fluid efficiency: 1-9 is the h = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9

High efficiency of hydraulic fracturing fluid means low filtration leakage during hydraulic fracture development. This allows the creation of high fractures because the stress intensity factor for an existing rock fracture is always higher than the critical stress intensity factor due to the high pressure in the fracture. Therefore, in this case, not so extended hydraulic fractures [12].

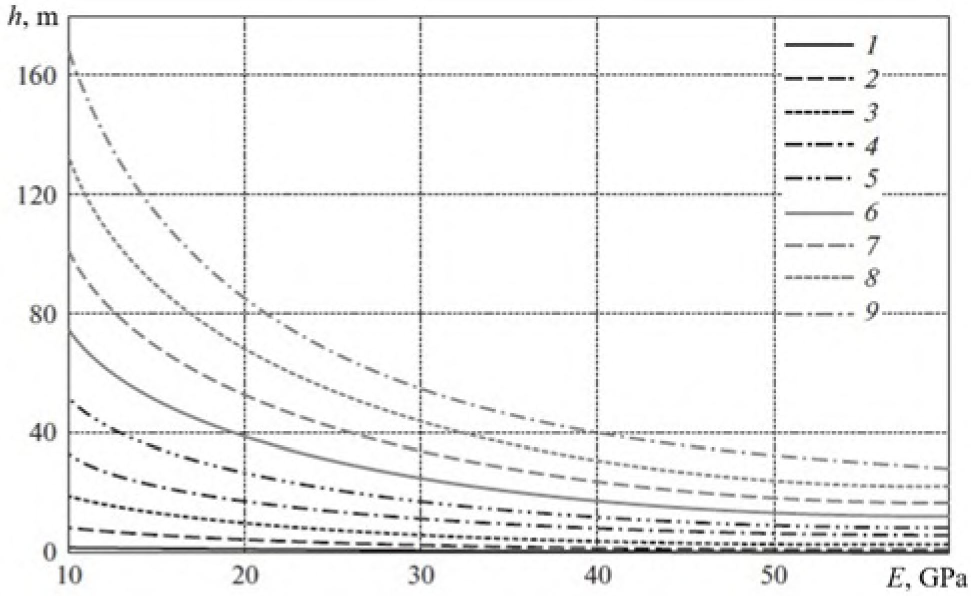

Figure 3. Dependence of fracture height on rock Young's modulus for different hydraulic fracturing fluid efficiency: 1-9 is the h = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9

Data on the probable fracture geometry obtained during research are necessary to predict subsequent flow rates, as well as the volume of injected proppant.

The geological characteristics of the rock also influence the choice of proppant needed to prevent the well from collapsing when the pressure decreases. There are three main groups of materials from which proppant is produced: sand, resin-coated sand, and synthetic ceramic materials (figure 4) [13, 14].

Figure 4. Types of proppants.

Types of proppants are also classified by no proppants, proppants of various fractions (12/18, 16/20, 20/40, etc.), tarred proppants, tagged proppants, lightweight proppants, weighted proppants, non-standard shaped proppants, elastic proppants, acid-resistant proppants.

Each type of proppant has its own characteristics that are suitable for different types of rocks (figure 5). Choosing the wrong proppant can lead to a significant reduction in the width of the well, or to destruction proppant [15, 16].

To carry out hydraulic fracturing correctly, it is necessary to calculate the pressure. Geological and technological indicators of the reservoir help to calculate the formation rupture pressure.

Proppant type	Density (g/cm^3)	Resistance (psi)
Pure sand	2.65	< 6.000 (~41 MPa)
Resin-coated sand (RCS)	2.55	< 8.000 (~55 MPa)
Intermediate resistance ceramic (IRC)	2.7-3.3	5.000-10,000 (34-69 MPa)
High resistance ceramic (HRC)	3.4	> 10.000 (69 MPa)
Bauxite	2.00	> 7.000 (48 MPa)

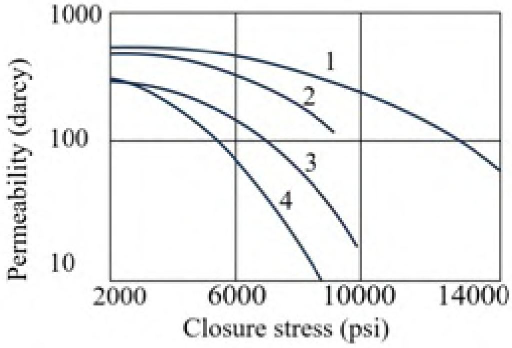

Figure 5. Proppant selection scheme depending on fracture closure stress: 1 – High strength proppant; 2 – Intermediate strength proppant; 3 – Resin-coated sand; 4 – Sand.

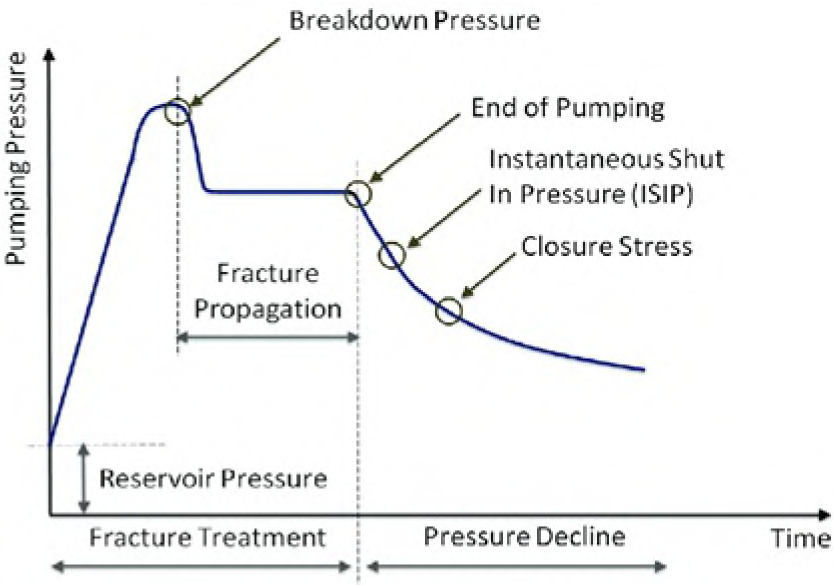

Figure 6. Scheme of pressure changes during a hydraulic fracturing operation.

During the operation, monitoring pressure changes at each stage helps to correctly carry out hydraulic fracturing and identify deviations (figure 6) [17].

An important step is also the selection of hydraulic fracturing fluid. It must satisfy certain physical and chemical properties. The fluid must be compatible with the formation material, could hold the proppant in suspension and transport it deep into the fracture, and must be easily removed from the formation after treatment [18].

Thus, the selection of optimal operating parameters includes the analysis of various parameters, including those that depend on each other. The overall effectiveness of hydraulic fracturing depends on the correct choice of each parameter. During the selection process, it is necessary to process a large amount of information, and therefore optimization of this operation is an important factor [19, 20].

These parameters include the choice of hydraulic fracturing type, selection of the appropriate type of process fluid and type of proppant material. These parameters directly affect the efficiency of hydraulic fracturing. Accordingly, it is necessary to approach the selection of the necessary parameters responsibly and consider all possible options [21].

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3. Methodology

Calculation and selection of hydraulic fracturing operating parameters is a complex task. Conventionally, they can be divided into two groups: static and dynamic. Static values include values that are calculated from available geological and technical data. Dynamic parameters include those parameters that can be changed during the hydraulic fracturing process to obtain the most effective result. Dynamic parameters can be selected and optimized considering specific tasks and features of hydraulic fracturing.

Let's consider the methodology for calculating the dynamic parameters of hydraulic fracturing:

1. Calculation of the vertical component of rock pressure:

$$P_{gv} = \rho_p g L_{sv}, \tag{5}$$

where L_{sv} is the well depth, m; ρ_p is the average value of the density of the rock lying from the surface to the bottom of the formation, kg/m^3; g is the free fall acceleration, m^3/s.

2. Calculation of the horizontal component of rock pressure:

$$P_{gg} = P_{gv}\frac{v}{1-v}, \tag{6}$$

where v is the Poisson's ratio of rocks.

3. Calculation of formation rupture pressure when using a non-filtering fluid:

$$P_p = P_{gv} - P_{pl} + G_p, \tag{7}$$

where P_{gv} is the vertical component of rock pressure, MPa; P_{pl} is the reservoir pressure, MPa; G_p is the rock tensile strength, MPa (G_p=1.5...3.0 MPa).

4. Calculation of the required bottomhole pressure:

$$P_{zab} = P_{pl}a, \tag{8}$$

where a is the required excess of bottom hole pressure over the burst pressure (a=1.2...1.4).

5. Calculation of the pressure required for hydraulic fracturing at the wellhead:

$$P_y = P_{zab} - P_{stl} + P_{tr}, \tag{9}$$

where P_{stl} is the static pressure, MPa; P_{tr} is the pressure loss due to friction, MPa.

6. Calculation of static pressure:

$$P_{st} = \rho_{sm} g L_{sv}, \tag{10}$$

where ρ_{sm} is the density of the mixture, kg/m^3.

7. Calculation of pressure loss due to friction:

$$P_{tr} = 1.52\lambda\frac{8Q^2 L'_{sv}\rho_{gp}}{\pi^2 d^2}, \tag{11}$$

where λ is the coefficient of hydraulic resistance; d is the internal diameter of the tubing, m.

8. Calculation of the coefficient of hydraulic resistance:

   - For turbulent mode ($Re > 2300$), the coefficient of hydraulic resistance is calculated using the following formula:

$$\lambda = \frac{0.3164}{Re}, \tag{12}$$

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- For laminar mode ($Re \leq 2300$), the coefficient of hydraulic resistance is calculated using the following formula:

$$\lambda = \frac{64}{Re}, \tag{13}$$

where Re is the Reynolds number.

9. Calculation of Reynolds number:

$$Re = \frac{4Q\rho_{sm}}{\pi d\mu_{sm}}, \tag{14}$$

where Q is the injection rate, m^3/s; μ_{sm} is the viscosity of the mixture, mPa·s.

10. Calculation of mixture viscosity:

$$\mu_{sm} = \mu e^{(3.18C)}, \tag{15}$$

where μ is the viscosity of the sand-carrying liquid, mPa·s.

11. Calculation of the total volume of injected fluid and the duration of the hydraulic fracturing process:
   (a) The volume of the fracturing fluid is determined by the following formula:

$$V_{gr} = \frac{L_{tr}^2 \left(P_{zab} - P_p\right) h}{E}, \tag{16}$$

   where L_{tr} is the half-length of the fracture, m; P_{zab} is the bottomhole pressure, MPa; P_p is the formation rupture pressure, MPa; h is the thickness of the formation, m; E is Young's modulus, MPa.
   (b) The volume of sand-carrying liquid is determined by the ratio:

$$V_{gp} = \frac{Q_p}{C_p}, \tag{17}$$

   where Q_p is the amount of proppant, kg; C_p is the proppant concentration, kg/m^3.
   (c) The volume of liquid in the pipes is determined by the following formula:

$$V_{pr} = \frac{K\pi d^2 L_{sv}^{'}}{4}, \tag{18}$$

   where K is a coefficient that considers the excess of liquid volume over the total volume of pipes (K= 1.3).

   The total volume of pumped liquid is determined by the following formula:

$$V_k = V_{gr} + V_{gp} + V_{pr}. \tag{19}$$

12. Calculation of vertical crack length:

$$L_t = \sqrt{\frac{V_{gp}E}{5.61\left(1 - v^2\right) h \left(P_r - P_{gg}\right)}}. \tag{20}$$

13. Calculation of the total duration of the hydraulic fracturing process:

$$V_k = \frac{V_g}{Q}. \tag{21}$$

14. Calculation of the technological efficiency of hydraulic fracturing.

(a) Calculation of hydraulic fracture radius:

$$r_{tr} = \sqrt{\frac{V_g E}{5.61\left(1-v^2\right) h \left(P_z - P_r\right)}}. \tag{22}$$

(b) Calculation of hydraulic fracture width:

$$w = \frac{4\left(1-v\right) r'_{tr} \left(P_{zab} - P_p\right)}{E}. \tag{23}$$

(c) Calculation of residual crack width:

$$w_{ost} = \frac{wC}{1-\mu_{tr}}, \tag{24}$$

where μ_{tr} is the fracture porosity (μ_{tr}=0.3).

(d) Calculation of fracture permeability:

$$K_{tr} = \frac{w^2}{12}. \tag{25}$$

(e) Calculation of the permeability of the bottomhole formation zone:

$$K_{pz} = \frac{K_p h + K_{tr} w}{h + w}. \tag{26}$$

(f) Calculation of the expected effect from hydraulic fracturing – oil production after hydraulic fracturing:

$$Q_n = \frac{2\pi K h \Delta P}{\mu_{gp}\left(ln\left(\frac{R_k}{r_c}\right)\right)}. \tag{27}$$

where R_k is the radius of the well supply circuit, m; r_c is the well radius, m.

(g) Calculation of the increase in oil production:

$$Q_e = q - Q_n. \tag{28}$$

where q is the average oil flow rate in the well before hydraulic fracturing, t/day.

4. Results

As can be seen from the calculation methodology, the correct selection of such parameters as the type, properties, concentration of the proppant, the type and properties of the sand carrier fluid, and the rate of injection of the mixture directly affect the efficiency of hydraulic fracturing. Therefore, the selection of the most appropriate operating dynamic parameters for hydraulic fracturing plays an important role. This process can be optimized to obtain better results.

To begin with, using the given methodology, calculations are carried out to determine the operating parameters of hydraulic fracturing. After this, the calculation and selection of dynamic hydraulic fracturing parameters begins.

First you need to select the process fluid. The type and concentration of fluid and additives depend on the formation temperature, lithology, and formation fluids.

Next, you need to select the required amount and type of proppant. There are three main proppant parameters that affect fracture conductivity: proppant concentration, proppant size, and proppant strength.

In the process of selecting the appropriate type of proppant, it is necessary to evaluate the magnitude of the closure stress cracks. This value can be calculated using the following formula:

$$P_h = \frac{v}{1-v} - (P_{gv} - P_p) + P_p, \tag{29}$$

where v is Poisson's ratio; P_{gv} is the vertical component of rock pressure, MPa; P_p is the pore pressure, MPa.

On drawing (figure 7) shows the dependence of the proppant type on the fracture closure stress. The proppant size must be selected considering the fracture closure pressure. Different types of proppants with the same granule size also have different effects on fracture permeability depending on the closure pressure [22].

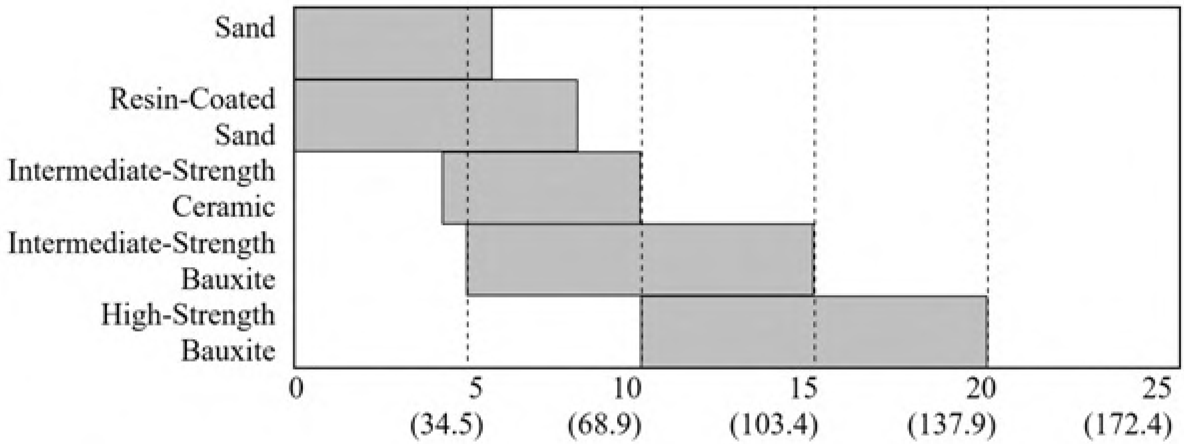

Figure 7. The principle of choosing the type of proppant.

The process of selecting the type of proppant needs to be optimized through automation, since it can be very time-consuming due to the analysis of many factors.

As a result of the analysis of these dependencies, the most effective types of proppants are identified, which are considered in the calculation, and among which the most suitable one is selected. Next, the optimal amount of injected proppant is selected.

The choice of injection rate is based on two principles. Firstly, a low injection rate is unacceptable because the fluid supply rate may be lower than its filtration rate. Secondly, too high an injection rate will lead to the formation of a turbulent regime in the pipes, which will increase pressure loss due to friction.

Substituting the selected parameters into the calculation and having variables in the form of the amount and type of proppant, we select the most effective type of proppant and the mass of injected proppant material [23].

All obtained operating parameters need clarification and can be adjusted after control hydraulic fracturing.

To ensure the accuracy and reliability of geomechanical data on the rock, a calibration test is carried out before the main hydraulic fracturing. Control fracturing is an important stage of on-site testing before the main fracturing operation and involves injection of fluid at a speed close to the main operation, using large volumes of fluid and a small amount of proppant. This allows you to set optimal parameters for further main hydraulic fracturing. Control hydraulic fracturing allows you to obtain the following data: formation closure pressure, closure stress, hydraulic fracturing fluid efficiency, effective pressure, fluid filtration parameters.

5. Conclusions

Considering all the nuances in the hydraulic fracturing process, the following sequence of actions is proposed for calculating and selecting operating parameters when carrying out hydraulic fracturing:

1. Selection, according to the geological features and tasks of the work, of the most suitable type of hydraulic fracturing to be carried out at the well.
2. Selection of the appropriate type and composition of the working fluid, considering the geological and technological features of the well.
3. Selection of the appropriate type of proppant. To optimize this process, it is proposed to use an automated algorithm, which should consider different brands of proppant material, select the most effective one for a specific calculation, and make it possible to quickly reselect the type of proppant when specifying the operating parameters.
4. Selection of the required amount of injected proppant. To optimize this process, it is necessary to consider the dependence of the geometric parameters of the fracture on the volume of injected proppant, based on previously carried out work. Next, you need to select a range of proppant amounts that can provide the required fracture parameters.
5. Calculate hydraulic fracturing, according to the above methodology, for several variants of operating parameters and select the most effective ones that will be used during the work.

This will speed up the process of calculating and selecting hydraulic fracturing operating parameters and carry out optimization, which will eliminate the need to calculate in advance ineffective hydraulic fracturing options. Also, this algorithm can be used as a basis for introducing automatic search and calculation of hydraulic fracturing in the field.

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Propagation of elastic waves in cross-sectionally heterogeneous rods

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Propagation of elastic waves in cross-sectionally heterogeneous rods

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Abstract. The article is devoted to measuring the propagation speed of elastic waves in metal rods of variable cross-section. The paper examines the dependence of the speed measure of propagation of elastic waves on the geometric and physical characteristics of the rods. The research methods are based on the use of known statements of the impact theory during the collision of a ball with the end of a metal rod. Solid rods, stepped rods, and rods with axisymmetric holes of different depths were experimentally studied. A piezo sensor connected to a digital oscilloscope was used to record pressure fluctuations at the end of the rod. The method of least squares was used for processing and further analysis of experimental data. Theoretical and experimental studies proved that there are two characteristic areas in which the speed of propagation of an elastic wave in a non-homogeneous cross-sectional rod differs from the value of the wave speed in a one-dimensional rod. A sinusoidal functional dependence of the propagation speed of the elastic wave on the caliber of the rod was obtained.

1. Introduction

The process of rods colliding with each other or with an obstacle, and also propagation of elastic waves in them is the subject of numerous theoretical and experimental studies. The physics of collisions related to wave propagation in elastic rods has been investigated for more than a century [1]. The number of works in this field is constantly growing, as the issues of modern mechanical engineering, military and mining force researchers to study deeper and deeper the internal regularities of the impact process.

In this regard, it should be admitted that the leading role in the study of phenomena associated with the impact of solid bodies currently belongs to experimental works. Thus, in paper [2] the contact time of metal rods bouncing off a steel plate was measured, the collision of balls and rods was researched in the article [3]. It is concluded that colliding steel rods, unlike steel balls, can lose kinetic energy during collisions. The lost kinetic energy manifests itself in the form of vibrational energy in the rods. But the reasons for which the steel balls collide elastically remained mysterious to the author. In paper [4], analytical and experimental results of experiments with rods were compared. In paper [5], the dependence of the recovery coefficient on the number of repeated hits of the ball on aluminum rods was studied. In paper [6], the results of experiments with bouncing balls, springs, and rods are presented. It was investigated what part of the initial kinetic energy is stored after the collision in the form of vibrational energy in the spring and rod.

The classical theory of the collision of solid bodies, created by a number of researchers, starting with Galileo, considered the collision of bodies as absolutely solid, and the collision process as instantaneous. This theory made it possible to determine only the result of the impact – the change in the speeds of the bodies. The internal regularities of the impact process – its duration (impact time), the amount of contact forces and deformations – remained undisclosed.

Hertz [7] managed to establish by calculation the dependence of the magnitude of the contact force and the duration of the collision of bodies on their masses and velocities before the impact, based on the hypothesis that the relationship between the contact force and the local deformation of bodies upon impact is the same as when they are statically compressed. Along with Hertz's theory, which takes into account only local deformations and does not consider the deformations of bodies far from the contact site, the theory of the impact of elastic bodies has been developed, which takes into account their general deformations and does not consider local deformations in the first moments of impact interaction.

The wave theory of shock, which is adapted to a longitudinal shock on a rod of constant section, was first proposed by Navier. The unsuccessful form of the solution in trigonometric series did not allow Navier to reveal all the features of the longitudinal impact and, above all, excluded the possibility of determining stresses. Later, Saint-Venant and Boussinesq [8] found a solution to the one-dimensional longitudinal impact problem using discontinuous functions, which made it possible to directly trace the propagation of deformation waves along the rod. The experimental verification of the shock wave theory conducted by a number of researchers did not give completely satisfactory results, which caused a critical attitude to the hypothesis of flat cross-sections and the neglect of the transverse movement of the rod particles, as well as the assumption that the collision surfaces are parallel planes. Existing deviations from the hypothesis of flat sections should be especially noticeable near the wave front; the presence of these deviations leads to the fact that the wave front gradually erodes, its steepness decreases. It is obvious that deviations from the hypothesis of flat sections will be more pronounced, the greater the ratio of the diameter of the rod to its length.

The insufficiency of both those theories that take into account only local deformations, but neglect general ones, and those that take into account only general and neglect local deformations, forced to look for a "synthetic" theory of impact, which would consider local and general deformations.

For the longitudinal impact, such a theory was developed by Sears [9]. Considering the collision of rods with spherical ends, Sears suggested that the hypothesis of plane cross-sections is valid for the entire rod, except for a small area near the end of the rod, within which the stress state is sharply inhomogeneous. Deformations of the area near the end of the rod are calculated using Hertz's formulas, and wave theory is used to calculate the rest of the rod. Sears' calculations were confirmed by experiments.

As can be seen from the above, the difficulties associated with the theoretical description of the impact process force us to introduce a number of simplified hypotheses, in most cases they are not sufficiently confirmed by experiments, and all methods of calculating the impact process are approximate.

Thus, in works by Gulidov et al. [10–12], numerical modeling of the rebound process of rods of finite length from an absolutely rigid obstacle, as well as the propagation of elastic waves in round rods in a two-dimensional setting, was carried out. The results of these works confirmed the influence of the rod dimensions on the propagation speed of the elastic wave and the time of contact with the obstacle.

When numerically modeling the rebound of axisymmetric rods from a solid obstacle, it is assumed that the speed of propagation of elastic waves in the rods is equal to twice the length of

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the rod divided by the contact time. At the same time, it is assumed that the contribution to the kinetic energy of the terms describing the transverse movement of the rod particles is very small. Since tangential stresses are not taken into account, the contribution of shear potential energy is also not considered. One-dimensional theory is used for such rods and the speed of wave propagation c in such rods is defined as $c = \sqrt{E/\rho}$, where E is Young's modulus of elasticity, ρ is the density of the material.

In order to prove the need to take into account transverse unloading waves coming from the side surface of the rod, in our experiments we use stepped rods with a variable step length, as well as rods in the form of a truncated cone with axisymmetric holes of different depths. The results of the experiments need prove the significant dependence of the propagation speed of elastic waves on the shape of the side and inner surface of the rods and thereby prove the fallacy of establishing the limits of calculating the stress-strain state of the rod in a one-dimensional approximation.

2. Research methods

To determine the optimal conditions for conducting experiments, the following was carried out:

a) analysis of the results of numerical modeling of the collision process of a rod of finite length with an absolutely rigid obstacle;
b) analysis of propagation of elastic waves in uniform round rods.

The following were experimentally carried out:

a) measurement of the duration of the impact and the speed of propagation of elastic waves in metal solid rods and rods of round stepped-variable cross-section;
b) measurement of the speed of propagation of elastic waves in metal rods of circular cross-section with axisymmetric holes of different depths.

Two methods of measuring the speed of elastic waves were used:

a) by the time of propagation of the elastic wave in the rod (recorder – piezo sensor);
b) by the time of collision of two rods (electrical contact method).

For this, three types of installations were used:

a) with bifilar suspension of rods;
b) using a guide chute
c) using a guide tube.

A Tektronix TPS2014B oscilloscope was used to simultaneously record the duration of electrical contact of the rods and elastic oscillations.

The purpose of the work was to obtain the dependence of the speed of propagation of elastic waves on the geometric and physical characteristics of the rods.

The research methods are based on the use of known provisions of the impact theory during the collision of a ball with the end of a metal rod. A piezo sensor connected to a digital oscilloscope was used to record pressure fluctuations at the end of the rod. The method of least squares was used for processing and further analysis of experimental data.

3. Results and discussion

Table 1 shows the characteristics of rod materials used in this work (ρ – density, K – volume modulus of elasticity, μ – shear modulus, λ – Lamé's constant, ν – Poisson's ratio, c_e – speed of elastic wave propagation in a one-dimensional rod, c_p – speed of longitudinal waves, c_S – speed of transverse waves, c_λ – speed of waves in a thin layer).

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Table 1. Characteristics of rod materials.

Material	$\rho \cdot 10^3$, kg/m^3	K, GPa	μ, GPa	λ, GPa	ν	$c_e \cdot 10^3$, m/s	$c_p \cdot 10^3$, m/s	$c_S \cdot 10^3$, m/s	$c_\lambda \cdot 10^3$, m/s
Aluminum	2.70	69	27	51	0.33	5.14	6.23	3.16	5.44
Iron	7.88	170	80	117	0.29	5.13	5.92	3.19	5.37
Copper	8.90	137	48	105	0.34	3.80	4.75	2.32	4.05

When the rod hits a rigid obstacle at the initial moment of time, the end of the rod comes into contact with the obstacle at all points and remains in contact with it for some time, after which it immediately or gradually separates from the obstacle. The time from the moment of contact to the moment when all points of the end of the rod move away from the obstacle is chosen as the contact time.

From the solution of the elastic problem about the contact of a one-dimensional rod with an obstacle upon impact, it is known that the contact time is:

$$t_K = 2L/c_e, \tag{1}$$

where L – the length of the rod.

In the general case, waves of several types with different velocities propagate in the rod as in a solid body. On the basis of equation (1), let us assume that a wave propagates in the rod with an unknown average speed, such that after the wave travels a distance equal to two lengths of the rod, the rod rebounds during the time t_K. Thus, the average wave speed can be found using the equation:

$$c = 2L/t_K. \tag{2}$$

and the contact time will be taken based on the results of work [13], where it was determined using the KRUG software complex, designed for the numerical solution of dynamic problems of mechanics. For certainty, consider the impact of a uniform rod with a diameter of $D = 10mm$ and a caliber of $L/D = 0.1/10.0$ against an absolutely rigid obstacle. There are no transverse stresses in the rod.

Figure 1 shows the calculated dependence of the relative average wave speed on the gauge for uniform aluminum rods [12] (c' – the ratio of the wave speed found by formula (2) to the speed c_e).

Analysis of the data presented in figure 1, allows us to draw the following conclusions:

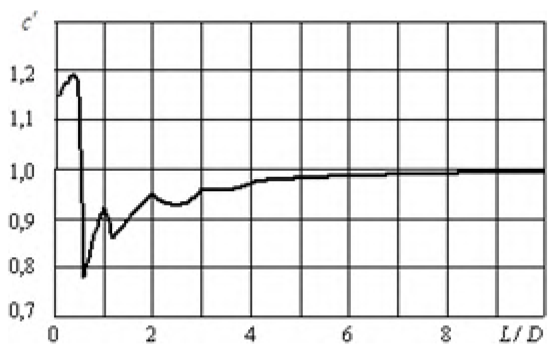

Figure 1. The dependence of the relative average wave speed on the gauge for rod.

a) at small values of the gauge of the rod ($L/D < 1$), the speed of wave propagation is close to the speed of longitudinal waves c_p (this is explained by the fact that slower transverse waves originating at the free cylindrical boundary do not have time to affect the longitudinal wave, the path length the spread of which is insignificant compared to the radius of the rod);

b) when the caliber increases, the average wave speed c goes towards the c_e speed (starting with a rod size equal to three gauges ($L/D = 3$) the ratio $c/c_e = 0.97$, i.e. the difference between the speed of the wave c and the speed of c_e becomes less than 3%);

c) there is such a gauge value ($L/D = 0.6$ for aluminum) at which the average speed of the longitudinal wave is minimal, which is due to the significant effect of transverse vibrations on it.

For each material, the minimum value of the average speed is different according to the caliber of the rod. To estimate the caliber at which the minimum relative average velocity occurs, we use the ratio of transverse and longitudinal velocities c_S/c_p, the value of which is a constant value for the material of the rod.

Figure 2 shows the dependence of the gauge value K_{min}, at which the wave speed reaches a minimum, on the c_S/c_p ratio for rods made of different materials [12]. From figure 2, it follows that the gauge of the rod, at which the minimum value of the wave speed is observed, increases with an increase in the value of c_S/c_p.

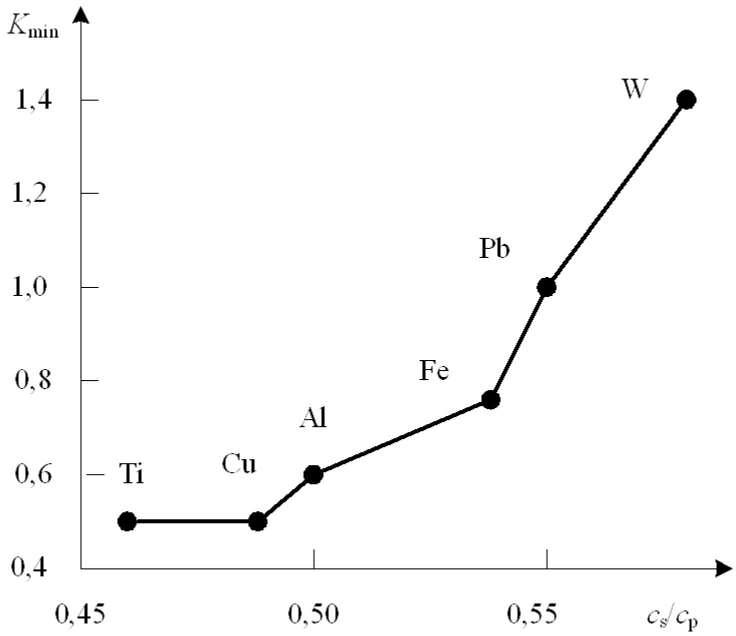

Figure 2. The gauge value at which the relative average speed minimum is observed.

The conducted analysis of the propagation of elastic waves in round rods shows that the value of the average speed of wave propagation in short rods differs from the speed of the wave, which is determined in the one-dimensional theory.

Therefore, when the wave is reflected from the end of the rod, the same processes and regions will appear at the other end of the rod. That is, hitting the other end of the rod will not change the pattern of changes in the speed of the elastic wave along the rod – it will be symmetrical.

These effects can be "manifested" by interfering with the aforementioned processes, for example, by reducing the diameter of the rod in these areas from D to d, forming a stepped rod,

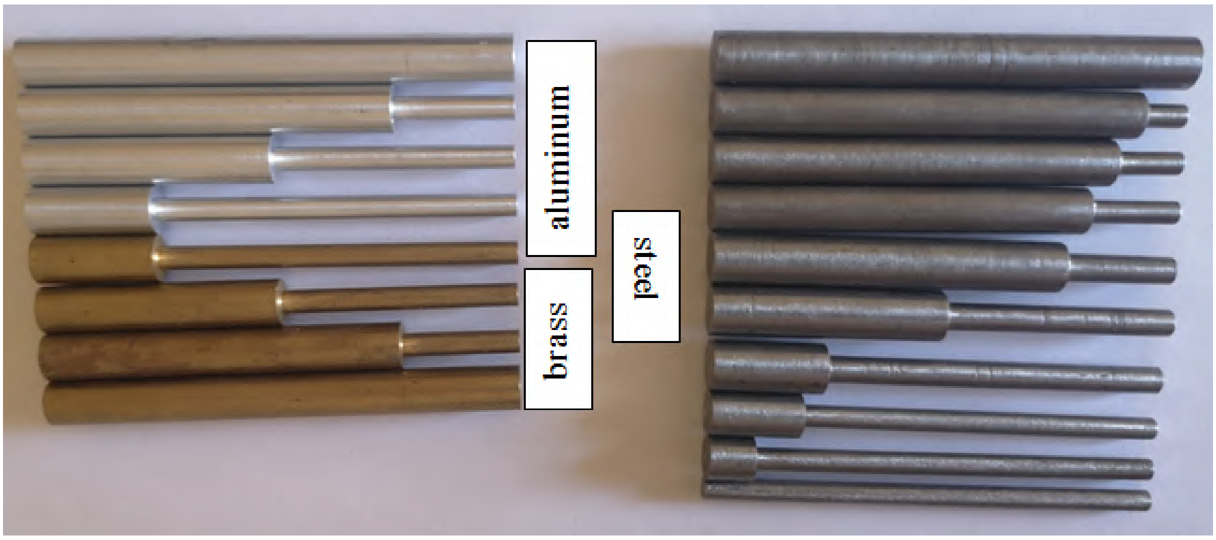

Figure 3. Photo of stepped rods.

or by reducing the cross-sectional area of the rod by making an axisymmetric hole of length l in it figure 3.

As experiments have shown, measuring the speed of an elastic wave on a bifilar type installation is not appropriate because it is impossible to ensure the parallelism of the ends of the rods upon impact and their alignment in most experiments. The error in determining the speed of propagation of an elastic wave by this method is up to 10%. The installation with a guide chute ensures the parallelism of the ends of the rods upon impact and their alignment. The error in determining the speed of an elastic wave in metal rods is up to 7%. The method of measuring the speed of elastic waves using a guide tube turned out to be the most accurate with an error of up to 1%. Therefore, exactly with the help of this method it was determined that the dependence of the speed of the elastic wave on the geometric and physical parameters of uniform and step-shaped rods and rods with axisymmetric holes.

To prove the possibility of controlling the speed of propagation of elastic waves, an experimental setup was made and research was carried out (figure 4).

The results of spectral and oscillographic measurements of the speed of elastic waves in steel are shown in table 2 [14] and graphs in figure 5 for steel, aluminum, brass.

Table 2. Results of oscillographic measurements (St3ps steel, density 7850 kg/m^3).

Caliber l/L	0	0.1	0.15	0.2	0.25	0.5	0.75	0.8	0.9	1.0
$\vartheta, m/s$	4932	5514	5840	5958	5899	4922	3985	4025	4301	4962

The results of oscillographic measurements of the speed of elastic waves in an iron rod with a hole of different depths are shown in the table 3 and figure 6.

4. Conclusions

Experiments proved that the propagation speed of an elastic wave in a rod of finite length depends on the shape of its side and inner surface. For stepped rods, there are two characteristic areas in which the velocity differs from the wave velocity in a one-dimensional rod by $\pm 20\%$.

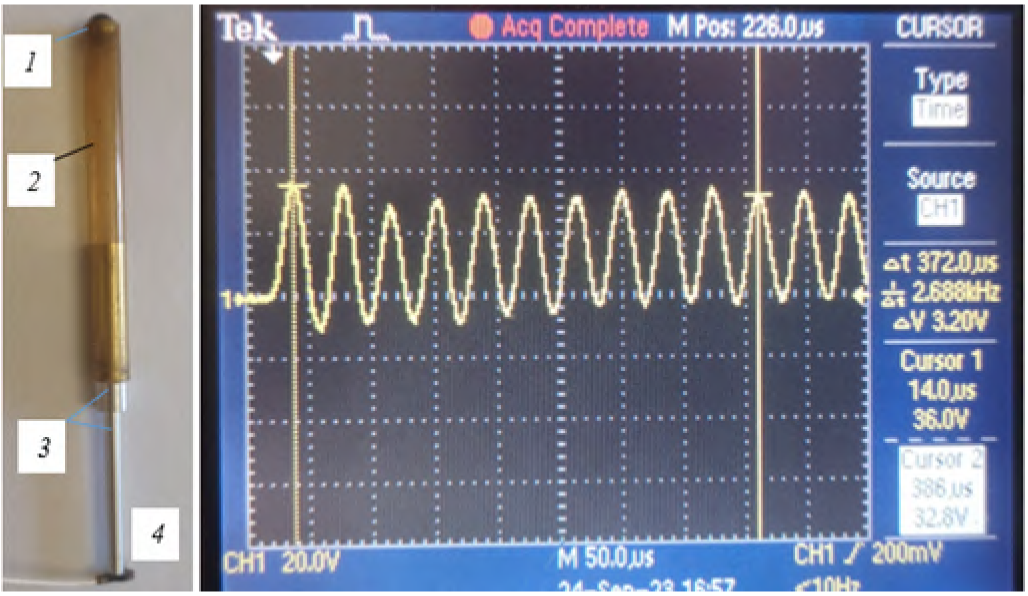

Figure 4. Photo of the research setup and oscillation oscillograms: 1 – metal ball, 2 – guide tube, 3 – rod, 4 – piezo sensor.

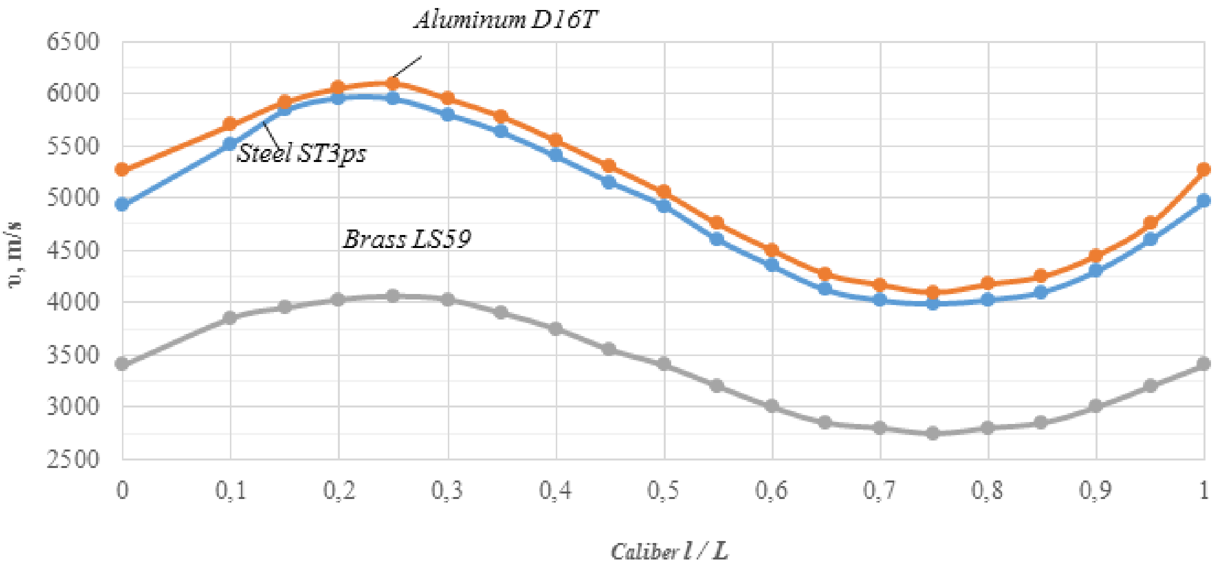

Figure 5. Dependence of the speed of elastic waves on the l/L ratio for a structural carbon steel of ordinary quality (1), aluminum (2), brass (3) rod with a diameter of 10 mm and a length of 100 mm, with a step diameter of 5mm and a length of l.

Table 3. Results of oscillographic measurements of the speed of elastic waves in an iron rod with a hole.

Caliber l/L	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$\vartheta, m/s$	5208	5319	5376	5376	5319	5208	5076	5025	5025	5076	5208

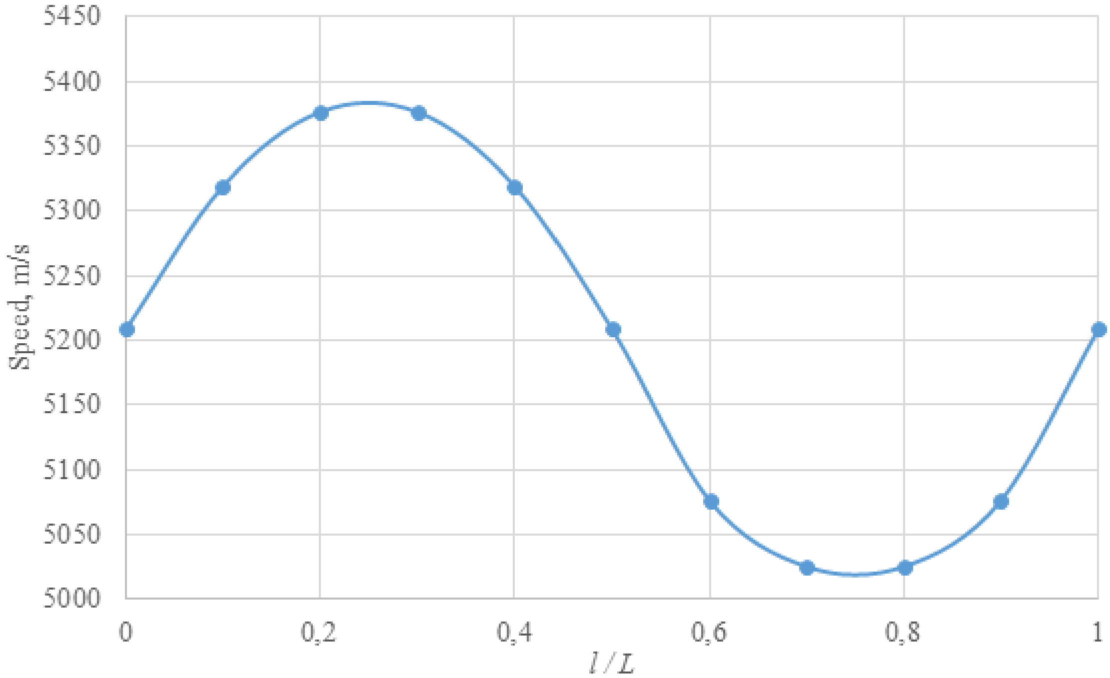

Figure 6. Dependence of the speed of elastic waves on the l/L ratio for an iron rod with a diameter of 10 mm and a length of 100 mm, with a hole diameter of 5 mm and a length of l.

The extreme speed of the wave reaches when the length of the step is about 0.25 and 0.75 of the length of the rod. For steel, the maximum speed was 5958 m/s, aluminum 6098 m/s, brass 4065m/s, the minimum speed was 4000 m/s for steel, 4098 m/s for aluminum, 2747 m/s for brass.

For rods with an axisymmetric hole, there are also two characteristic areas, in which the velocity differs from the value of the wave velocity in a one-dimensional rod by $\pm 3\%$. The extreme speed of the wave reaches when the depth of the hole is about 0.25 and 0.75 of the length of the rod. For iron, the maximum speed was 5376 m/s, the minimum speed was 5025m/s.

The results of these works confirmed the influence of the shape of the variable cross-section of the rod on the speed of propagation of the elastic wave.

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PAPER • OPEN ACCESS

Comparison of the seismic loading of points on the surface of the Earth during a massive explosion in a mine

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Comparison of the seismic loading of points on the surface of the Earth during a massive explosion in a mine

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Abstract. Geomechanical studies are performed at almost all large mining enterprises in the world. As a result of industrial activity, the Kryvyi Rih region has developed serious environmental problems. The mining of ore in Kryvyi Rih region led to the formation of numerous underground cavities. Hundreds of square kilometers of the Earth's surface were in zones of mass collapse. Therefore, diagnosis and control of the stress state of the massif of rocks are relevant. Along with the processes of movement of underground cavities to the Earth's surface, there is a constant threat of destruction or damage to residential buildings, violation of the integrity of the massif due to mass explosions in quarries and mines. These explosions also affect the rate at which voids emerge. This leads not only to unpredictable exits of funnels and the development of landslides, but also to the threat of rock strikes in mines. The article considers the method of measuring the vector velocity of soil particle oscillations from one source in different directions at the same time.The purpose of this article is to compare the seismic load of points on the Earth's surface during an explosion in a mine with their orthogonal location along the directions under the conditions of destruction of the rock body in a separate area. The main task of the research was to determine the intensity of seismic explosion vibrations near the foundations of residential buildings and industrial buildings in the area of the industrial site of the mine, which were located in opposite directions. The main result of the work is obtaining a set of data related to the amplitude and frequency characteristics of seismic waves that have passed through a half-kilometer layer of rock.

1. Introduction

At the end of 2023, the Laboratory of Explosion Management and Mining Seismics of SRMI of Kryvyi Rih National University (KNU) carried out instrumental measurements of the level of impact of seismic vibrations generated by a massive explosion carried out in a mine on residential buildings. Performed seismic observations are part of the general monitoring of the magnitude of seismic fluctuations during blasting operations at mining enterprises. The purpose of the research was to compare the seismic load of points on the Earth's surface during an explosion in a mine with their orthogonal location along the directions in the conditions of the destruction of the rock body in a separate area. The main task of the research was to determine the intensity of seismic explosion vibrations near the foundations of residential buildings and industrial buildings

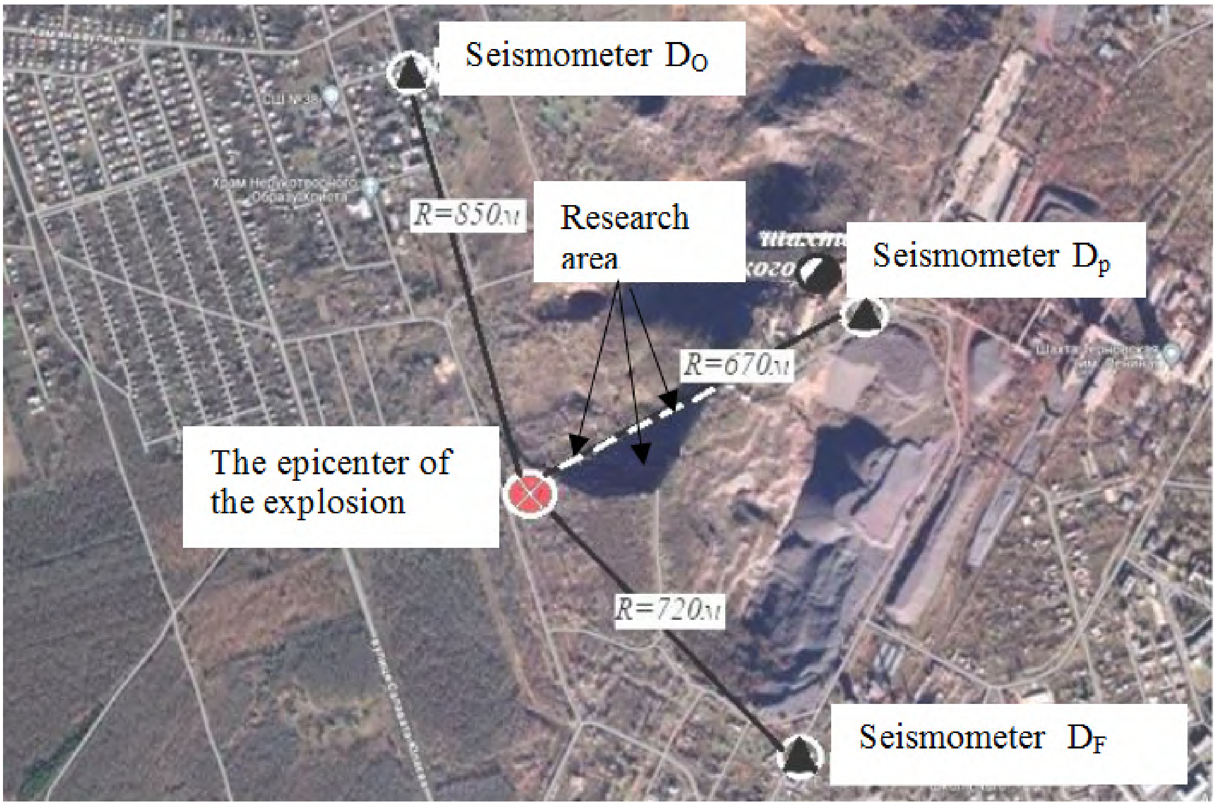

Figure 1. Surface plan of the research area with the location of seismometers on the Earth's surface, the epicenter of the explosion, residential buildings.

in the area of the industrial site of the mine, which were located in almost opposite directions (figure 1).

The intense vibration of residential buildings caused by blasting in mines and quarries is one of the fundamental problems for residents and the environment [1]. The presence of subsurface voids in the areas of ore mining leads to their movement with subsequent collapse of the surface of the Earth (figure 2).

Therefore, reliable forecasting of the state of rock, especially near residential buildings and industrial structures, is an urgent task. It is very important to learn how to control the vibration in such difficult conditions caused by blasting operations in order to mitigate their negative effects. The negative impact of vibration cannot be completely eliminated, but it can be reduced to a safe level.

A massive explosion in a mine generates seismic waves on the Earth's surface with different maximum particle velocities and a wide range of frequencies. This process depends on 1) rock properties, 2) charge parameters and 3) blasting technology. If we want to control the condition of the rock under residential buildings and structures located near the destruction zones, it is necessary to constantly experimentally determine the propagation speed and frequency spectrum of seismic waves from blasting. On the other hand, on the basis of experimentally determined parameters, it is possible to determine the optimal technology of blasting works so that there are no economic losses for the mining enterprise.

Parameters of a mass explosion. The mass explosion at a depth of 387-527 meters was carried out using the technologies of blasting with well charges. The well charges were detonated in short bursts. The number of wells is about 220. The total mass of used granulated and cartridge

Figure 2. Land collapse with the destruction of housing (photo by Archil Svanidze).

explosives was 44 tons. So, on average, the charge of the well was 0.2 t (the estimated specific rate of expansive substance is about 0.41 kg of ES per 1 ton of mining mass).

2. Object and methods of research

It is possible to monitor the development of geomechanical processes by various methods of observation [2, 3]. One of the methods of research is based on the principle of dependence of the properties of rocks and their stress-strained state on the magnitude of the influence of force fields arising in the massif. Therefore, a significant part of research is aimed at evaluating the strength, elastic, rheological, electromagnetic, acoustic and other physical and mechanical properties of rocks. But the problem of operational search for underground cavities can be solved directly by measuring the speed of propagation of seismic waves throughout the rock layer, i.e. instrumentally. As an example of the implementation of this principle, the article considers the method of measuring the vector velocity of soil particle oscillations from one source in different directions at the same time.

During seismometric observations, SM-3 seismographs and Tektronix TPS-2014 oscilloscopes were used. The main environmental criterion of the seismic hazard of an explosion is the intensity of the seismic wave, which can cause damage to the structures of buildings [4–7]. The magnitude of the vector velocity determines the density of the energy flow, therefore, as a characteristic of energy, it is directly related to the conditions of damage to structures. Damage to the protected object occurs if sufficient energy penetrates into it from the seismic wave. Without this energy, damage cannot occur, even if the force characteristics exceed those required for this in the case of statics. Therefore, the measurement of seismic parameters was carried out in this experiment by recording the vector velocity of soil oscillations (figure 3, figure 4).

The formula that determines the vector speed:

$$\vartheta = \sqrt{\vartheta_x^2 + \vartheta_y^2 + \vartheta_z^2} \tag{1}$$

where ϑ_x, ϑ_y, ϑ_z are the maximum instantaneous speeds in the direction of the x, y, z axes: the y axis was directed to the epicenter of the explosion.

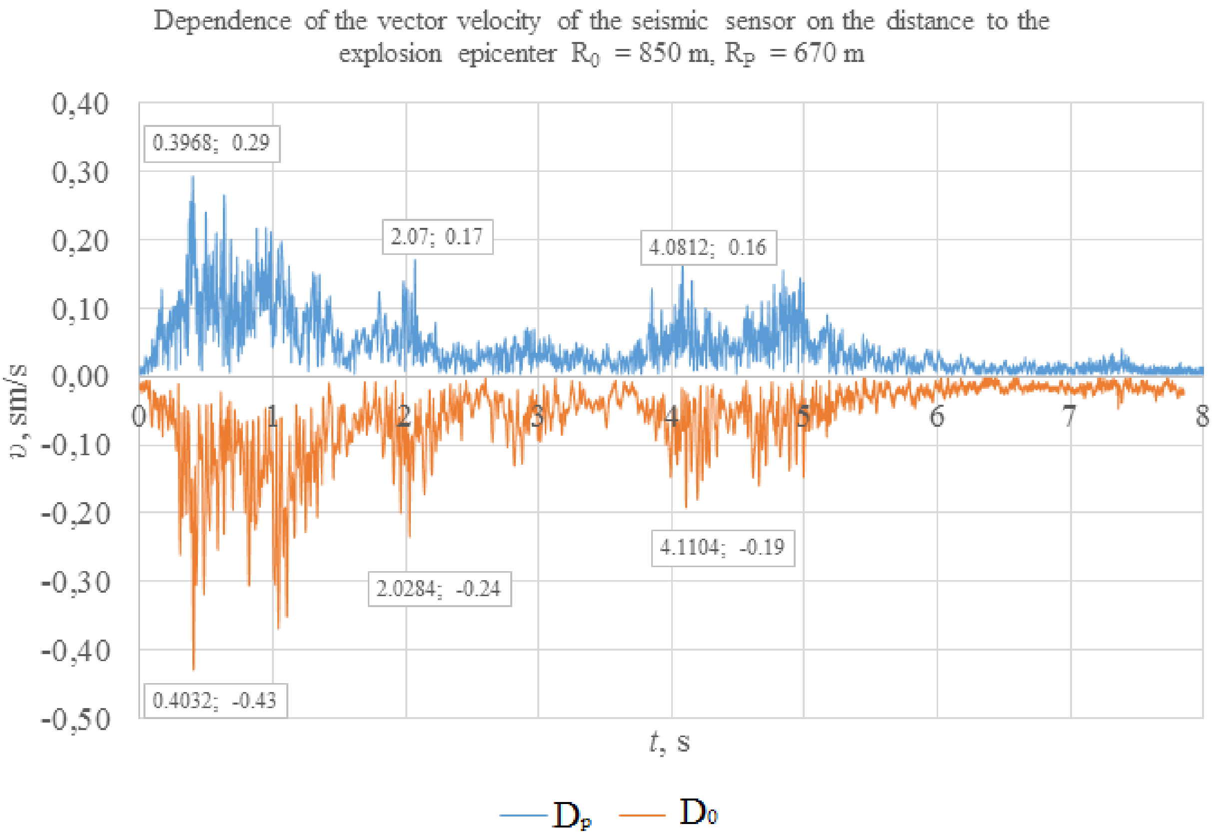

Figure 3. Comparison of seismograms obtained at different observation points: the D_P seismometer was located behind the rock destruction zone at a distance of 670 meters from the epicenter of the explosion, D_0 – at a distance of 850 meters near a residential building.

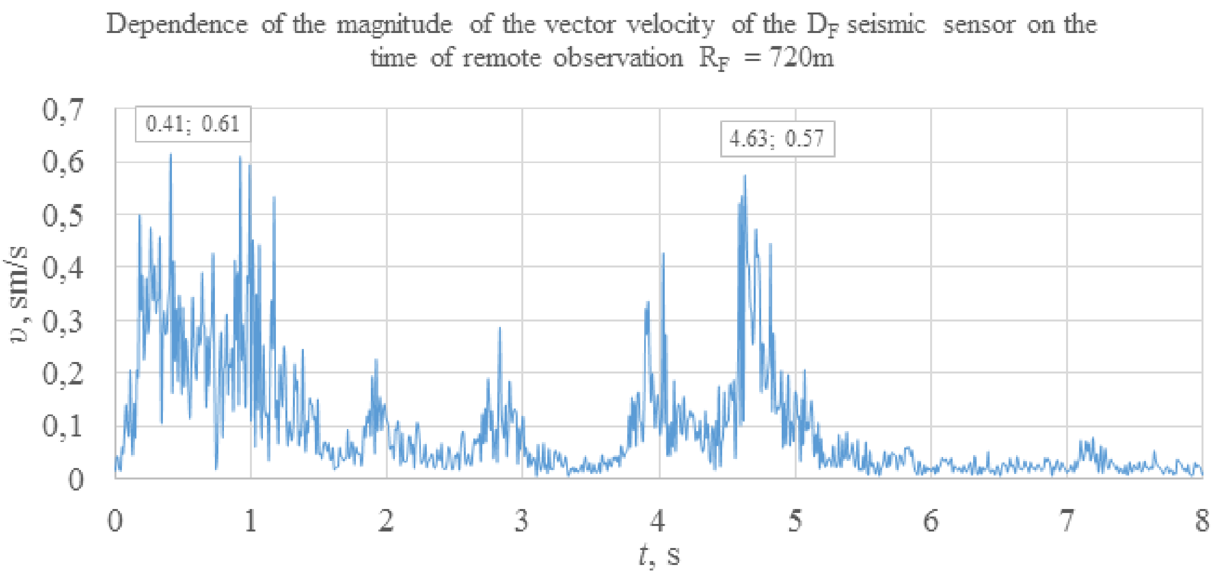

Figure 4. The graph of the change in the vector velocity of the D_F seismic sensor, located at a distance of 720 meters from the epicenter of the explosion near the house.

Since the maximum instantaneous speed is set in different directions not simultaneously, the vector speed does not refer to any common for all moments of time: the moments of reaching the maximum instantaneous speeds and cannot coincide in time in principle.

3. Results and discussion

The duration of ground vibrations was close to 6 seconds. It is noteworthy that the shape of the signals is almost identical (figure 3), but the values of the maximum speed differ: at a shorter distance from the explosion, the amplitude is almost 1.5 times smaller. To explain this phenomenon, it is necessary to obviously recognize that the existing fractured area between the blasting wells and the D_P observation point acts as a screen. It is known that when seismic waves collide with a cavity in rock, a phenomenon called refraction occurs. Part of the energy of the waves is reflected back, and part is refracted and continues to move. This leads to a change in the speed and direction of wave propagation, which is reflected on seismic oscillograms and can be used to monitor the geological structure. The oscillogram obtained from the third seismic sensor of the D_F also confirms this regularity (figure 4, table 1).

Table 1. Measurement results.

	D_O	D_F	D_P
H, m		387-527	
R, m	850	720	670
r, m	994	817	774
ϑ, sm/s	0.43	0.61	0.29

The value of the maximum vector speed registered by the D_F seismometer was 0.61 sm/s, which corresponds to 3 points and almost more than 2.1 times the maximum speed registered by the D_P seismometer and 1.4 times more that registered by the D_0 seismometer. So, we can see the clear influence of the rock structure on the amplitude of oscillations of soil particles near the foundations of residential buildings, the dependence on the direction of seismic wave propagation. The influence of these factors is also observed in the works of other researchers. Thus, in the work [8] as a conclusion is indicated on the the fact that the maximum values of the speed of soil particles depend on a large number of various factors.

Although the distance to the industrial site was the shortest, due to the passage of seismic blast waves through the collapse zone and the loss of explosion energy, the lowest speed of ground vibrations was recorded at this registration point.

To explain the obtained non-trivial results, a frequency examination of the obtained oscillograms was carried out. Their frequency spectrum was studied (figure 5, figure 6, figure 7). The results of spectrogram processing are given in table 2.

Table 2. The results of processing spectrograms.

Seismometer	Frequency, Hz						
D_O	5.7	7.3	10.7				
D_P			10.7	12.5	15.3	19.2	
D_F				13		20	29.5

According to the results of frequency studies, it can be concluded that there is some correlation in the region of more than 10 Hz between the frequency properties of seismic signals

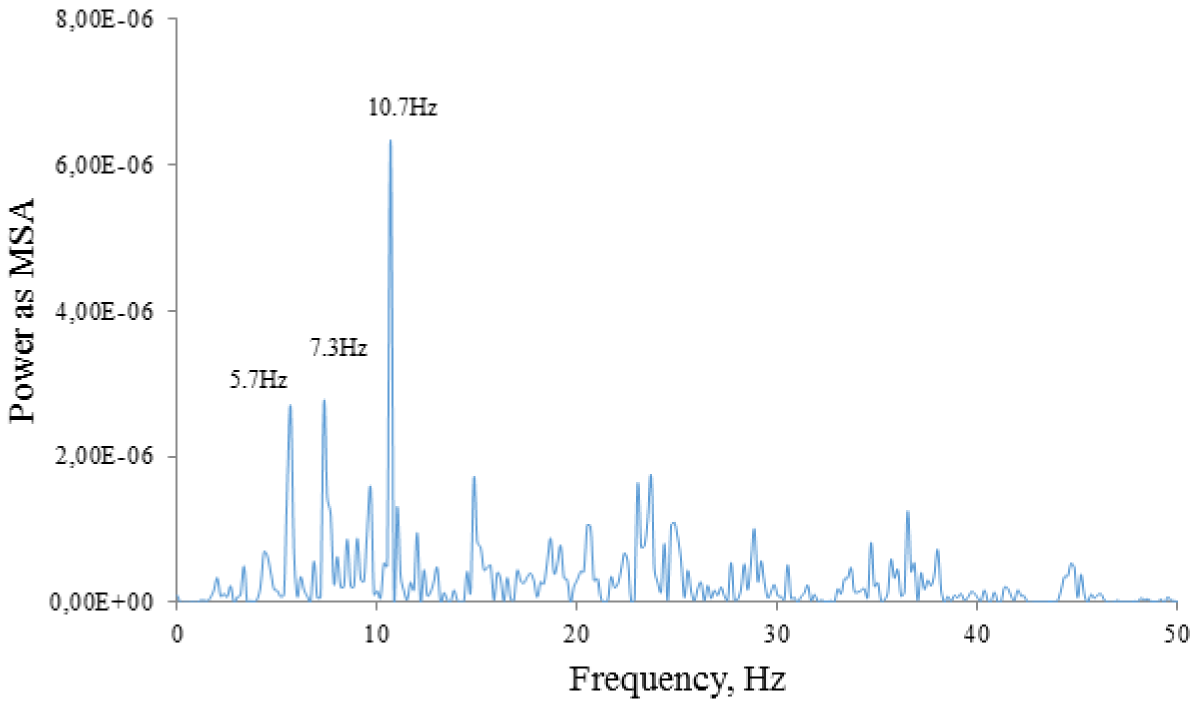

Figure 5. Spectrogram of seismic sensor D_0.

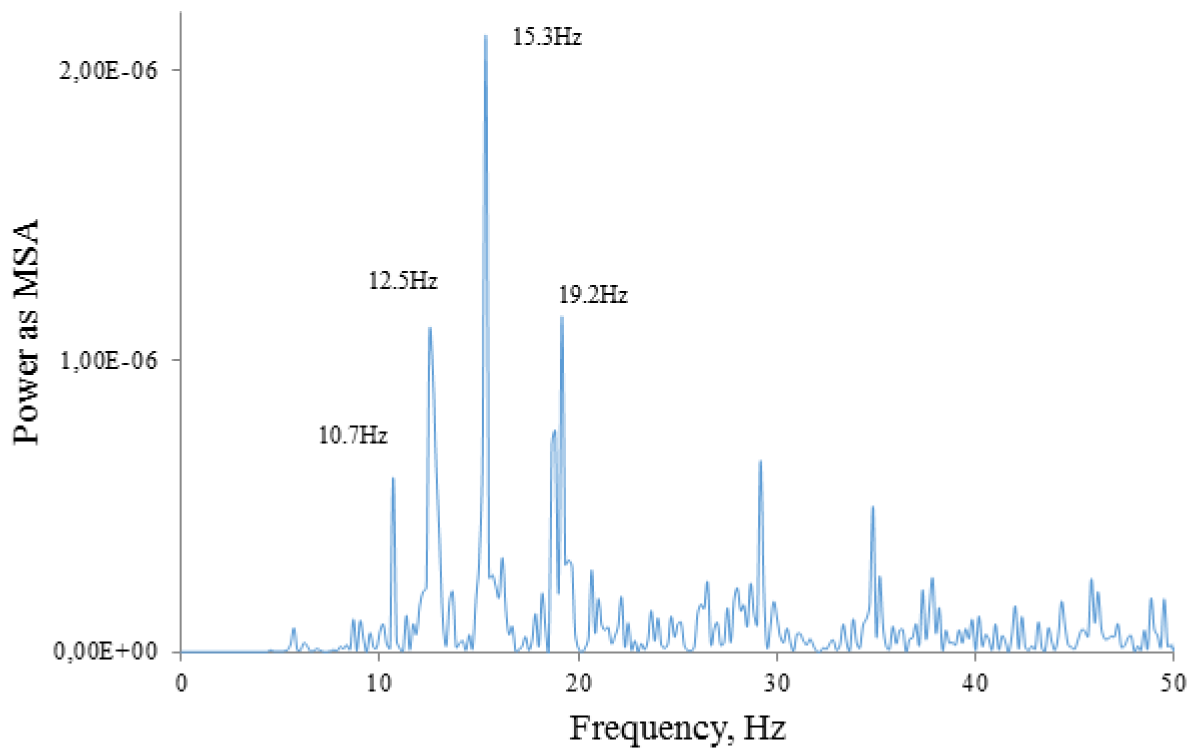

Figure 6. Spectrogram of seismic sensor D_P.

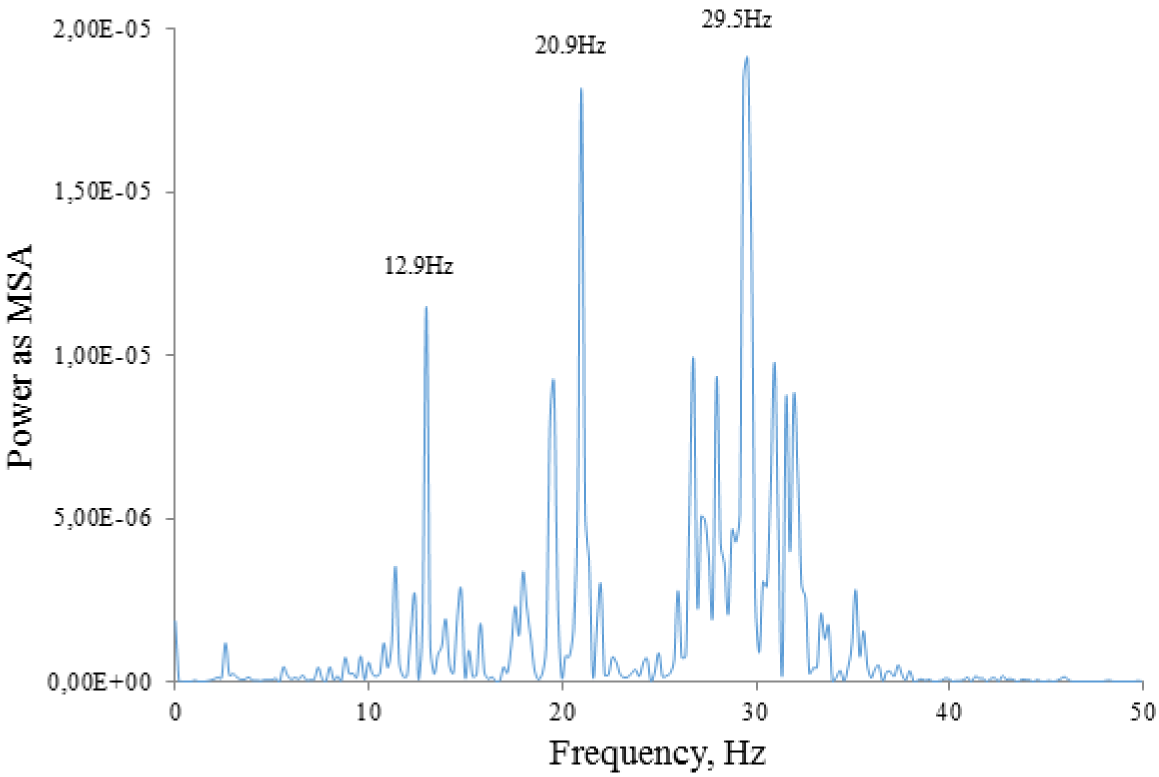

Figure 7. Spectrogram of seismic sensor D_F.

from D_P and D_F sensors installed on different sides of the rock massif destruction zone (figure 1). Such a correlation between the signals of the D_P and D_O sensors is not observed, which indicates a different structure of the massif that the seismic waves from the same source passed through. And this experimental fact provides a method of monitoring the structural changes of the massif.

4. Conclusions

The method of simultaneous measurement of the vector speed of oscillations of soil particles on the daytime surface from one underground source of seismic waves is considered.

A comparison of the seismic load of points on the surface of the Earth during an explosion in a mine with their orthogonal location along the directions in the conditions of the destruction of the rock body in a separate area was performed.

The intensity of seismic explosion vibrations near the foundations of residential buildings and industrial buildings in the area of the industrial site of the mine, which were located in orthogonal directions, was determined.

It has been proven that the intensity of seismic waves that have passed through a half-kilometer layer of rock is not determined by the known laws of their attenuation in a homogeneous environment, but entirely depends on the structure and properties of the rock. Studies of the frequency characteristics of seismic signals have also confirmed this fact.

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Modeling the process of ensuring environmental sustainability of the airport as a functional component of socio-tecnical systems

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Modeling the process of ensuring environmental sustainability of the airport as a functional component of socio-tecnical systems

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Abstract. The article addresses the modernization and broadening of the functional capacities of airport infrastructure, focusing on transforming airports into contemporary and ecologically safe spaces within socio-technical systems. This theme is not only pertinent for mitigating the adverse environmental effects of airports but also for enhancing the living conditions and health of the surrounding communities, airport personnel, and waiting passengers. The implementation of the ecologically safe space model yields positive economic outcomes, bolstering the airport's image and competitiveness among investors and the public. The paper introduces an original model for ecologically safe airport spaces, offering new avenues for the development and integration of innovative technologies to optimize environmental safety. The analysis covers economic, political, technological, and environmental factors influencing airport operations and their impact on the country. A range of measures is explored to minimize the negative environmental impact of airports, forming ecologically safe spaces within airports in line with international agreements, including the Airport Carbon Accreditation program. Positive examples of zero carbon emission airports and those evolving as city-airports are examined. The core of the work lies in devising a model for economically safe airport spaces based on a mathematical model of socioium activity within a specific sector of the airport's environmental framework. This dynamic model addresses complex issues such as reducing the airport's negative environmental impact on human within airport confines to prevent accidents, and minimizing the cyclic interaction level among airport stakeholders.

1. Introduction

The demand for air transportation is continuously growing, necessitating the modernization and expansion of the functional capabilities of airport infrastructure. An airport, as a functional component of modern socio-technical systems, is characterized by a "unique" spectrum of transportation services provided to passengers and cargo.

The airport's activities shape an ecological "footprint" in the geographical space of the surrounding environment, characterized by high levels of atmospheric pollution and volumes of "noise pollution". The current situation adversely affects the societal well-being and highlights the existing problem of low environmental safety in airports. Consequently, there is increasing pressure on the operations of airlines and airports to comply with environmental standards.

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Regulatory requirements for reducing emissions and improving environmental parameters are becoming increasingly stringent, compelling professionals to seek and implement new solutions to create environmentally safe airport spaces [1].

The establishment of an environmentally safe space will not only reduce the impact on the surrounding environment but also improve living and health conditions for residents around airports, airport personnel, and passengers awaiting their flights.

The strengthening of regulatory requirements for environmental safety necessitates airports to develop and implement models aimed at ensuring both ecological and economic efficiency in their operations [2]. Creating an environmentally safe airport space will enable the implementation of "smart" control over the volume of expenditures on environmental compensations and taxes, contributing to the improvement of the financial stability of airport operations.

Therefore, the modeling of an environmentally safe space for airports becomes crucial, opening new possibilities for the development and implementation of innovative technologies and methods aimed at optimizing the ecological safety of airport operations. It can serve as a tool to enhance public perception of airport activities, a key factor in increasing their competitiveness. As experience shows, airports that adopt an environmentally safe space model enhance their image and competitiveness in the eyes of both passengers and investors and the general public.

Hence, researching the issue of modeling an environmentally safe space for airports as socio-technical systems is relevant and has practical implications.

2. Literature review

Research on various aspects of airports' impact on the environment and the formation of an environmentally safe space is presented in recommendations of the International Civil Aviation Organization (ICAO), European Commission, US Federal Aviation Administration and publications by domestic and foreign scholars.

Among the international requirements and recommendations regulating issues of atmospheric air pollution during operation of aviation transport systems, it is noteworthy to mention:

- ICAO Standards and Recommended Practices: Annex 16, Volume II (2022) [3];
- Doc 10184, Assembly Resolutions in Force (ICAO, 2022) [4];
- ICAO Appendix A: Traffic Forecasts (ICAO, 2021) [5];
- Innovation for a Green Transition/2022 Environmental Report (ICAO, 2022) [6];
- Sustainable and smart mobility strategy: Putting European transport on track for the future (EU, 2021) [7];
- Report from the Commission to the European Parliament and the Council: Updated Analysis of the Non-CO_2 Climate Impacts of Aviation and Potential Policy Measures Pursuant to EU Emissions Trading System Directive Article 30(4) (European Union Aviation Safety Agency, 2020) [8];
- United States: 2021 Aviation Climate Action Plan (Federal Aviation Administration, 2021) [9].

Zaporozhets et al. investigated the impact of aircraft engine emissions on the state of air and the health of residents in the surrounding areas of the airport. They developed approaches to regulate air pollution during operations of aviation transport systems [10].

Kovalchuk examines the issue of preserving the natural environment within airport boundaries, focusing on ways to reduce their negative impact [11].

In the study conducted by Radomska et al., an analysis of soil contamination and phytomass due to the operation of air transport was carried out. Among the primary issues identified, an extremely high level of soil pollution by petroleum products and an elevated content of heavy metals were observed [12].

Omuya and Nkolo [13] analyzed the main spectrum of functional tasks faced by airports (safe landing and takeoff of aircraft; ground handling of aircraft; passenger and airport user management; ground transportation and airport access management; maintenance of buildings, installations, equipment). They also determined the degree of its environmental impact and identified sources of air pollution within airports. The authors emphasize the necessity of implementing effective environmental management through pollution prevention and managing the negative impact.

Xiong et al. [14] analyzes the functions of various institutions regarding the scale and intensity of their impact on airport operations to reduce their pollution potential deserves attention. The authors have developed a concept for modeling institutional causes of external effects on the airport.

The examined works provide a general overview of the environmental "footprint" from airport activities. However, the optimization of expenses for creating an environmentally safe space and ensuring environmental safety for individuals within the society (residents in the vicinity of the airport, airport personnel, passengers) in the geographical space where airports are located has not been adequately addressed in scientific literature, which outlines the problematic nature of this research.

3. Research purpose

In order to solve the problem of ensuring the environmental sustainability of the airport as a functional component of socio-technical systems, the article forms a block of primary tasks that need to be solved:

- analysis of the impact of airports on the basic sectors of the economy of Ukraine with the disclosure of their general characteristics in order to assess the state of the system: "airport-ecological component", using the example of total emissions of carbon dioxide and nitrogen oxides, as chemical elements forming the ecological "footprint" of the activity of airports;
- substantiating the basic priorities for the formation of an environmentally safe space at the airport, as vectors that determine ways to improve its functionality not only as a component of the socio-technical systems of the state, but also from the standpoint: the airport is a complex regional socio-technical system;
- development of a mathematical model for determining the necessary level of costs aimed at ensuring the activity of society's unit in a specific spatial sector of the architectural and spatial framework of the airport itself, taking into account the existing norms of environmental safety.

Based on the formed spectrum of tasks for solving the specified problem, the purpose of the article is the development of conceptual foundations for ensuring the environmental sustainability of the airport as a functional component of socio-technical systems and the mechanism for determining costs aimed at ensuring the activity of society's unit in a specific spatial sector of the architectural and spatial framework of the airport itself with taking into account the existing norms of environmental safety.

4. Results and discussion

The environmentally safe space (ESS) represents an environment where special attention is given to measures for preserving and improving ecological and environmental safety. It encompasses industrial facilities, residential areas, natural resources, and other components where ecological aspects are considered to avoid or minimize negative impacts on nature, human health, and interaction with the natural environment.

The subject of this study is the environmentally safe space of airports. Since airports are a vital component of the modern transportation system and the economy of any country, facilitating rapid and efficient movement of goods and passengers over long distances, contributing to the development of tourism, trade, business, and investments.

The functioning of airports is influenced by economic, political, technological, and ecological factors. Economic factors include the country's economic development, the level of tourism and international trade, fuel costs, etc. Economic growth leads to increased passenger and cargo traffic, requiring the expansion of airport networks and the modernization of their infrastructure, and vice versa. Political factors involve international relations, legislation, aviation-related restrictions linked to military conflicts. Political changes can lead to alterations in aviation routes, airport closures, or even destruction, as witnessed in Ukraine where 11 airports were damaged or completely destroyed due to missile attacks and warfare.

Technological factors encompass advancements in aviation, construction, and other fields. Technological innovations can reduce greenhouse gas emissions and noise from aircraft, expanding their use for cargo and passenger transportation.

Ecological factors include the state of the environment and requirements for its protection. Strengthening ecological standards may lead to additional economic costs but can also ensure a reduction in environmental pollution in airport areas.

If we analyze the impact of airports on the country's economy, we can distinguish the following directions: business and investments; international trade; tourism and the recreational sector; the creation of new jobs (table 1).

Table 1. Impact of airports on the country's economy.

№	Direction of influence	Characteristic
1	Business and investments	Airports, as centers of business activity, provide access to international markets, fostering business development and investments in the country.
2	International trade	Airports ensure a fast and reliable means of transporting goods and cargo between countries. According to the International Air Transport Association, in 2022, over 700 million tons of cargo were transported through airports worldwide, a 15% increase compared to 2021.
3	Tourism and the recreational sector	The presence of airports in a country contributes to the growth of tourist traffic. According to the World Tourism Organization, in 2022, airports worldwide served over 4.5 billion passengers, a 10% increase compared to 2021.
4	The creation of new jobs	The development of airports allows for the creation of new jobs for professionals in various fields, including aviation, infrastructure, construction, trade, and services.

Analyzing airport operations from an environmental impact perspective allows for the identification of both advantages and disadvantages in their functioning. Positive environmental impacts include fuel efficiency and the reduction of air pollution. On the other hand, negative environmental impacts encompass greenhouse gas emissions, noise pollution, and environmental pollution (table 2).

Table 2. Analysis of the ecological impact of the operation of airports.

Positive environmental impact	Negative environmental impact
Fuel efficiency	Greenhouse gas emissions
Air pollution reduction	Noise pollution
	Environmental pollution

The positive environmental impact of aviation lies in the fact that it is currently one of the fastest and most energy-efficient means of transportation. Compared to other modes of transport, airplanes emit less pollution per unit of cargo transported, contributing to a reduction in air pollution, especially when airports are located far from residential areas.

Flying is one of the most carbon-intensive activities – yet it contributes just 2.5% of the world's carbon emissions (figure 1). But air transport has contributed around 4% to global warming to date. Along with emitting CO_2, aircraft also affect the concentration of other atmospheric gases and pollutants (ozone and methane, water vapor, soot, sulfur aerosols, and water contrails) [15].

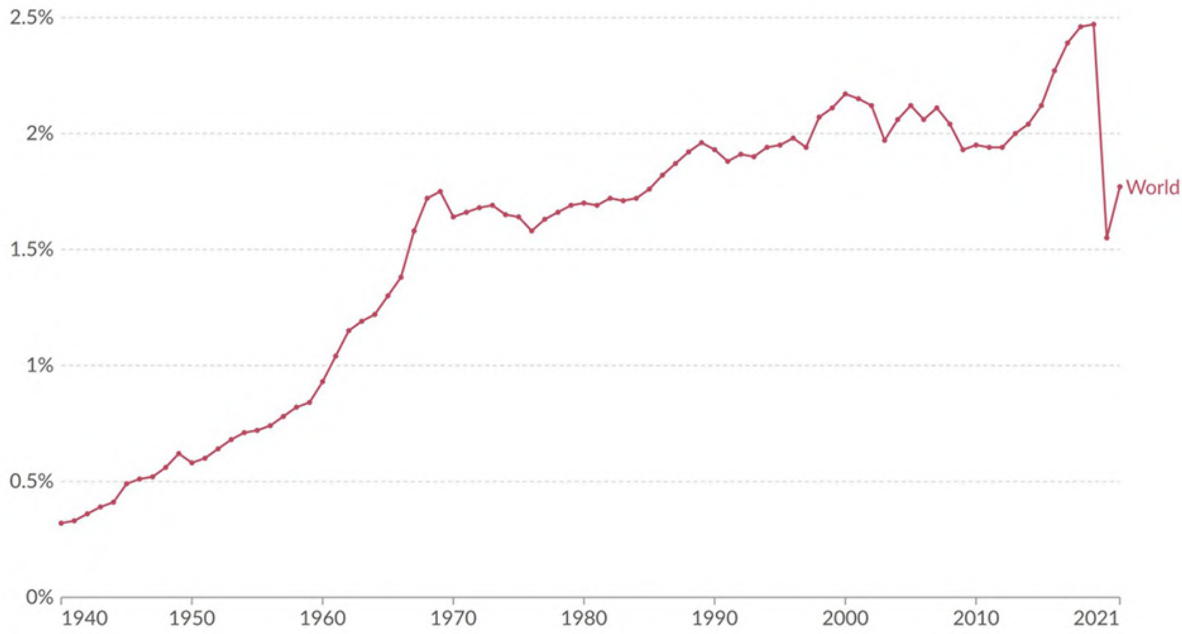

Figure 1. Aviation's share of global CO_2 emissions, 1940 to 2021 [15].

If we analyze the negative environmental impact, aviation is one of the largest sources of greenhouse gas emissions globally. According to the International Air Transport Association, in 2022, airports worldwide accounted for approximately 2.5% of all global greenhouse gas emissions. In turn, due to global warming, the hydrological cycle is changing, which can lead to alterations in precipitation and runoff patterns, affecting water availability. Many regions in Europe are already facing serious water shortages. Water use is typically considered a constraining factor for the growth of many airports [16].

The operation of aircraft generates noise, which can be harmful to human health. Airports can pollute the environment with waste, spent fuel, and other environmentally hazardous substances [13]. The predominant sources of air pollution within the airport are aircraft. The component of emissions from aircraft engines at the local level exceeds 50% of the total mass of pollutant emissions in the airport zone [10]. Soil analysis reveals high contamination with total petroleum hydrocarbons on runways and fuel storage areas. The content of heavy metals is significant, showing a high level of contamination with manganese, copper, lead, zinc, chromium, and iron compared to background soils outside the airport's influence [12].

To mitigate the negative impact of airports on the environment, a comprehensive approach is necessary. This includes improving airport planning and management, transitioning to more environmentally friendly fuel types compared to traditional ones, and developing and refining aircraft manufacturing technology. The possibilities for preserving the natural balance significantly expand when viewing the airport not just as a facility where passengers temporarily stay but as an airport hub. For instance, I Kovalchuk proposes considering the airport hub as a "small city with its 'population', residential and transport infrastructure, administration, and other elements of 'urban' life, where the construction of energy-efficient buildings, emission restrictions, the use of ecological materials in construction, educational activities to increase responsibility for environmental quality, and other initiatives can significantly improve the ecological situation at the airport". Since airport infrastructure consumes a massive amount of energy and water, comparable to the consumption of tens of thousands of households, and generates a large amount of waste, not to mention the scale of the territory it occupies, disrupting the migration paths of animals and birds, the evaluation of the airport's ecological impact is exceptionally important [11].

At the same time, regulatory interventions have always had a significant impact on the transportation industry, and issues related to the environment have been a crucial reason for such interventions. By establishing environmental restrictions, governments can help control/limit the burden of air transport and the harmful impact it may have on human health and the environment [17].

The establishment of an environmentally safe space within the airport boundaries is of paramount importance (figure 2).

In 2009, the Airports Council International (ACI) approved the Airport Carbon Accreditation program, aiming to assess aviation hubs in terms of their environmental impact. The goal was to reduce the negative impact of airports on the environment and transition the maximum number of aviation hubs to a carbon-neutral balance, effectively making them "neutral". In 2015, the Paris Agreement on climate and an international industry-wide Carbon Offset and Reduction Scheme for International Aviation (CORSIA) program were adopted. CORSIA outlines the procedures and opportunities for compensating the negative impact of airports on the eco-environment.

For the certification of buildings and structures according to environmental and energy efficiency requirements, well-known standards such as LEED (USA), BREEAM (UK), and the German standard DGNB exist. New airport terminals can be constructed according to various standards, depending on the country and the choices of designers. Additionally, there are international ISO standards for environmental management (14001), energy management (50001), greenhouse gas emissions (14064), and others, defining the qualitative characteristics of materials and technologies. Concerning airports, the Airport Carbon Accreditation program stands as the sole initiative exclusively focused on them [11].

Currently, there are 49 airports worldwide with a carbon-neutral status, with 40 located in Europe, 1 in the USA, 1 in Latin America, 1 in Australia, and 4 in India. The first international airport to achieve carbon-neutral status in 2009 was Stockholm Arlanda, serving 27 million passengers annually. In Ukraine, there is no such airport. However, it is crucial to initiate progress in this direction, as demonstrated by the management of 270 airports across various countries that have implemented measures for monitoring, assessment, and reduction of their

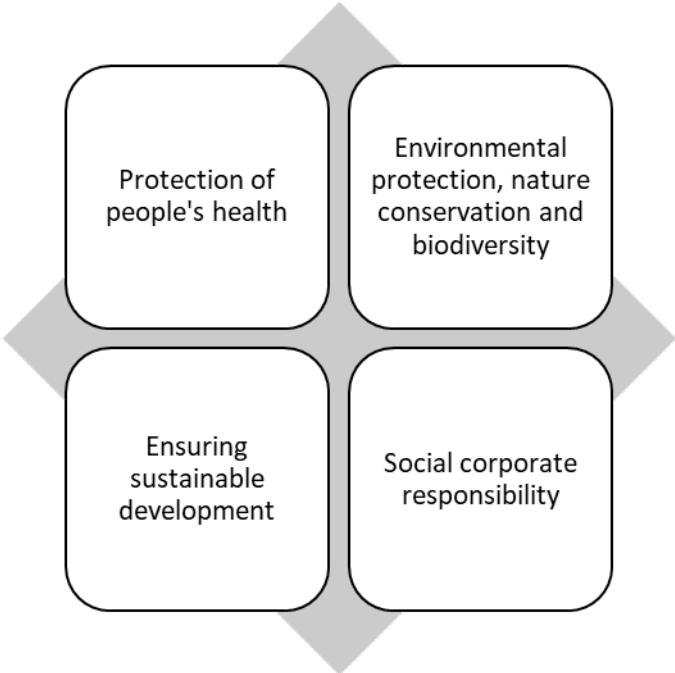

Figure 2. Priorities for the formation of an ecologically safe space at the airport.

environmental impact.

An interesting example is the airport in Helsinki, which is not only carbon-neutral but also follows the city-airport concept known as Aviapolis Vantaa. Therefore, it is essential for the airport to maintain a comfortable environmental setting in the surrounding area. To reduce emissions, the airport employs a range of measures, including the use of renewable energy sources (solar panels, wind turbines), LED lighting, infrastructure construction and reconstruction in line with BREEAM certification, utilization of biofuels, and collaboration with partners. Furthermore, Finavia, the company managing not only Helsinki but also 20 other airports in Finland, plans to completely reduce controlled CO_2 emissions across the entire network by 2020 [11].

It is also worth noting that Budapest Airport becomes the first airport in Central Europe to achieve Level 4+ Transition. It expands its fleet of electric vehicles and develops its e-charging infrastructure; covers 100% of the airport's total electricity consumption by renewable energy sources; has reduced its direct carbon emissions by more than 70% over the last decade and has excelled in waste management, recycling 73% of its municipal and packaging waste in 2023; pays special attention to the materials used for de-icing aircraft, roads, taxiways, and aprons, the fuel consumption of subcontractors during construction and development works, and the management of waste and wastewater to decrease negative environmental impact [18].

Ukraine must consider the impact of international agreements and conventions; therefore, the restoration and reconstruction of Ukrainian airports in the post-war period should occur based on environmentally safe principles, aligning with the principles of sustainable development. Specifically, ensuring an environmentally safe space helps avoid the negative impact of aviation activities on the health of the local population, including the reduction of noise levels and emissions of harmful substances. Protecting the health of airport personnel reduces the incidence of occupational diseases. Modern environmentally safe airports aim to minimize the adverse effects of aviation activities on the natural environment, passengers, and their health.

The restoration of Ukrainian airports with a focus on environmental safety involves the use

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of energy-efficient technologies and practices. In the long term, this contributes to reducing energy consumption and limiting greenhouse gas emissions. Creating an environmentally safe space involves considering the impact on nature and taking measures to preserve biodiversity and natural resources. Adhering to environmental standards during airport restoration will help preserve and restore local biodiversity. Green zones, the use of environmentally friendly materials, and the creation of natural ecosystems will contribute to the conservation of species diversity. Developing airports on environmental principles includes the application of innovative technologies to reduce environmental impact. This may involve the use of solar panels, the implementation of electric transportation, and other green initiatives.

Environmental standards in airports help create a sustainable space that can easily adapt to changes in regulatory requirements, using modern approaches to reduce environmental impact. The restoration of Ukrainian airports based on environmental principles will attract passengers and investors for whom this is a priority. This will ultimately have a positive impact on shaping the country's tourist image and promoting tourism development.

The formation of an environmentally safe space in Ukrainian airports enhances their image as a responsible corporate player considering the impact of activities on the environment and ready to implement environmentally effective solutions. The result of creating an environmentally safe space at the airport is ensuring the harmonious development of the aviation industry based on principles of safety, sustainability, and environmental responsibility.

An airport, as a socio-technical system, combines a complex of technical, technological, economic, social, and environmental components aimed at ensuring the efficient and safe operation of passenger and cargo aviation services. This system includes:

- Airport infrastructure includes runway systems, terminals, baggage systems, security checkpoints, airport ground transportation systems, and other technical elements that ensure the airport's operation.
- Aviation technologies encompass radio navigation systems, automated air traffic management systems, safety systems, and monitoring systems.
- The social factor involves airport personnel, administration, security services that facilitate the interaction and seamless operation of the airport, and, of course, passengers.
- Financial and economic aspects are related to the management and operation of the airport.
- The system for assessing and reducing the negative impact of aviation activities on the environment, including emissions reduction and resource optimization by the airport.

Thus, an airport is an integrated socio-technical system that operates in a highly dynamic environment, where all elements interact to achieve the main goal – ensuring safe and efficient aviation traffic services.

The safety of the ecological space of the airport represents a state of the environment where there is a balance between the process of ensuring the functionality of the ecological framework architecture and the process of neutralizing all types of negative impact from airport activities on the environment, with the obligatory implementation of the life cycle of all participants in air transportation.

The environmentally safe space for a societal unit within the geographical boundaries of airports can be presented not only by its coordinates in geographical space but also by its location concerning the technogenic component of the environment.

The technogenic component of the ESS in the studied environment is considered not only as a geographical plane occupied by humans but also as a functional sector in society, determined by the ecological potential of humans and dependent on the concept implemented in modern conditions of world development, namely, the concept of a "Healthy City".

The development of the ESS model for airports is based on a mathematical model of the societal unit's activity in a specific sector of the ecological framework architecture of the airport itself [19].

Such a model will help answer various questions, namely: what are the reasons for the decrease in human potential within the airport's existing boundaries, leading to accidents and disasters; reasons for the reduction in the level of cyclical interaction between the components of airport subjects and others.

The functionality of the ESS can be determined by the characteristics of processes aimed at reducing the negative environmental impact of the airport on humans and presented as a dynamic system model (figure 3). Processes aimed at ensuring the functionality of the ESS are presented taking into account the deficit in expenses to ensure the environmental safety of the societal unit's life, synthesized by the operation of transport within airports over a specified time interval.

Factors determining the functionality of the ESS are provided by the permissible range of

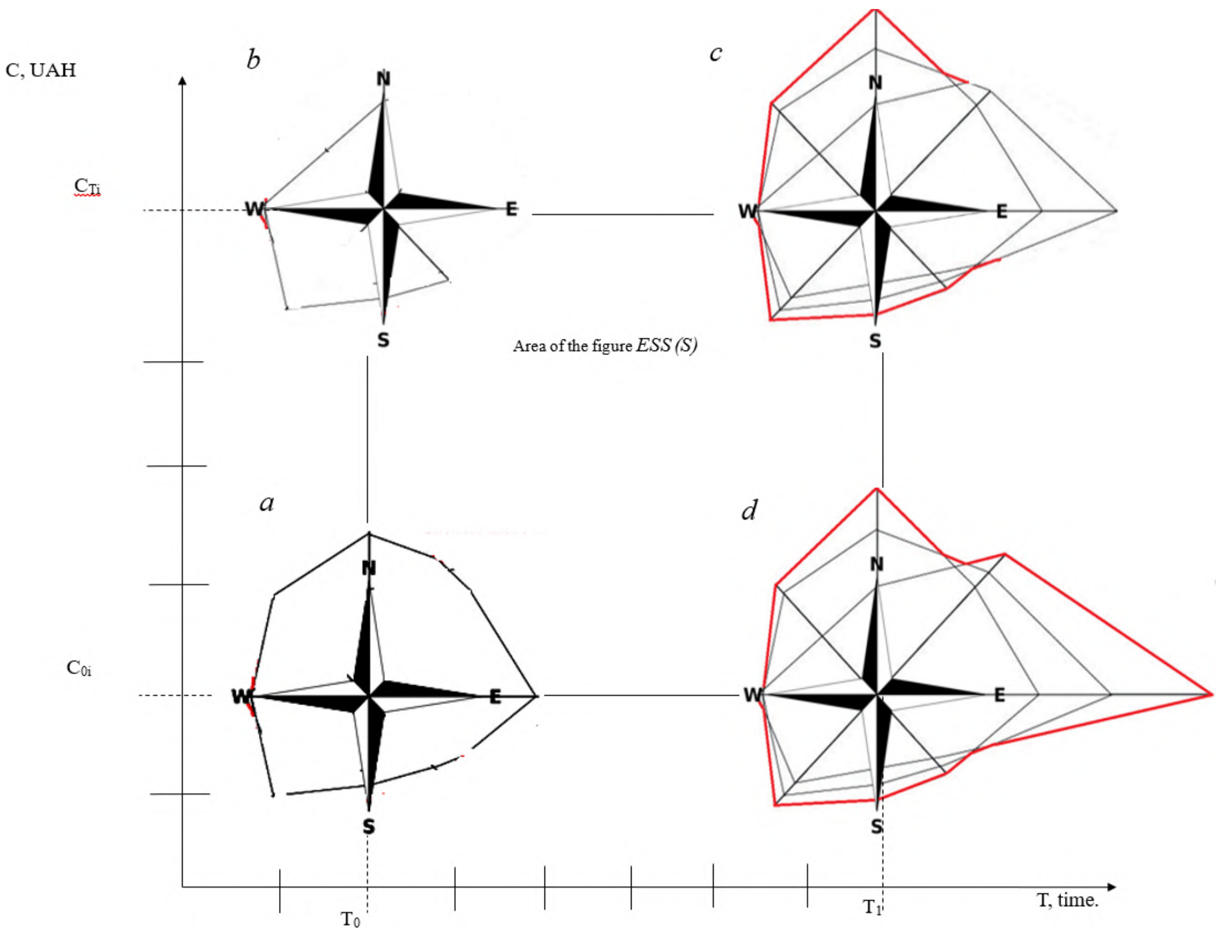

Figure 3. The schematic representation of changes in the ESS indicator $C_{0i} - C_{Ti}$ over time $T_0 - T_1$ in a two-dimensional space by the i-th factor – the level of ESS potential as a component of the ecological framework architecture.
"a-d" – a segment of high functionality of the ESS associated with a low level of deficit in expenses to ensure the environmental safety of the societal unit C's life;
"b-c" – a segment of low functionality of the ESS associated with a high level of deficit in expenses to ensure the environmental safety of the societal unit C's life.

state values (deficit level) $C_{0i} - C_{Ti}$ over the specified time interval $T_0 - T_1$.

Processes aimed at ensuring the functionality of the ESS are presented taking into account the deficit in expenses to ensure the environmental safety of the societal unit's life, synthesized by the operation of transport within airports over a specified time interval.

Factors determining the functionality of the ESS are provided by the permissible range of state values (deficit level) $C_{0i} - C_{Ti}$ over the specified time interval $T_0 - T_1$.

The model development is based on analytical geometry in a two-dimensional coordinate system. Due to the complexity of coordinating dimensions, relative indicators of these quantities in fractions of one unit will be considered in the future, and the magnitude of their changes Δ will be determined by the absolute value.

For simplification of the calculation, the process occurring in the ESS will be characterized by the area of a rectangle (S) formed by segments ΔC and ΔT in the considered two-dimensional coordinate system.

$$S = \Delta C \cdot \Delta T. \tag{1}$$

Based on the mathematical analysis, the area of the rectangle formed by ΔC and ΔT can be determined by the expression:

$$S = \int_{C_0}^{C_1} f(c)dC \tag{2}$$

In this case, we consider that $f(C_0) = T_0$, and $f(C_1) = T_1$. One of the main tasks of minimizing the risk of ESS in airport conditions is to reduce the deficit of the i-th factor (the level of ESS potential) C_{1i} to C_{ni}, i.e., determining $f(C_i) \to C_{ni}$. In the conditions of the ecological framework of airport entities, it can be assumed that $C_{oi} = C_{ni}$ (C_{ni} – the planned indicator set by the budget of the territorial community or other documents for the i-th factor). In this case, the parameter (T) is determined by the working and rest conditions of the employee.

However, for the regulation processes, the parameter is the physiological condition of a person F, which is also functionally related to factors $(C_{0i}, \cdots, C_{1n})$. The efficiency of the regulation process, determined by the level of deficit in expenses to ensure the environmental safety of the societal unit's life (O), will be defined by the magnitude measuring these factors. Changes in ESS factors (ΔC) will be determined by the indicators of expenses (resources) per unit (ΔS) of the "processed" volume of ESS.

The ESS of a person with a system for regulating its factors can be imagined in a three-dimensional coordinate system (figure 4). The volume of a parallelepiped or array formed by the corresponding vectors (C_i, C_d, C_f) will determine the result – compliance with normative requirements for the qualitative indicators (state) (O) of a person's ESS. C_i – the level of assimilation potential; C_d – the assessment of potential; C_f – the volume of consumption of the "dirty resource". The volume of the parallelepiped constructed on vectors is equal to:

$$O = C_i \cdot C_d \cdot C_f = (c_{2f} - c_{1f}) \cdot (c_{2i} - c_{1i}) \cdot (c_{2d} - c_{1d}). \tag{3}$$

The mathematical model, whose functional involves assessing the deficit of economic resources necessary to ensure the environmental safety of the societal unit in ESS as a component of the geographical space of airports, can be formulated in vector form in the algebraic projection of the cube's volume, by moving it to the origin and determining the coordinates of vectors:

$$C_d = \{0, 0, C_{2d}\}, C_i = \{0, C_{2i}, 0\}, C_f = \{C_{2f}, 0, 0\}. \tag{4}$$

The determinant (Δ) of the third order follows from the expression:

$$\Delta = x_1y_2z_3 - x_1y_3z_2 + y_1z_2x_3 - y_1z_3x_2 + z_1x_2y_3 - z_1x_3y_2, \tag{5}$$

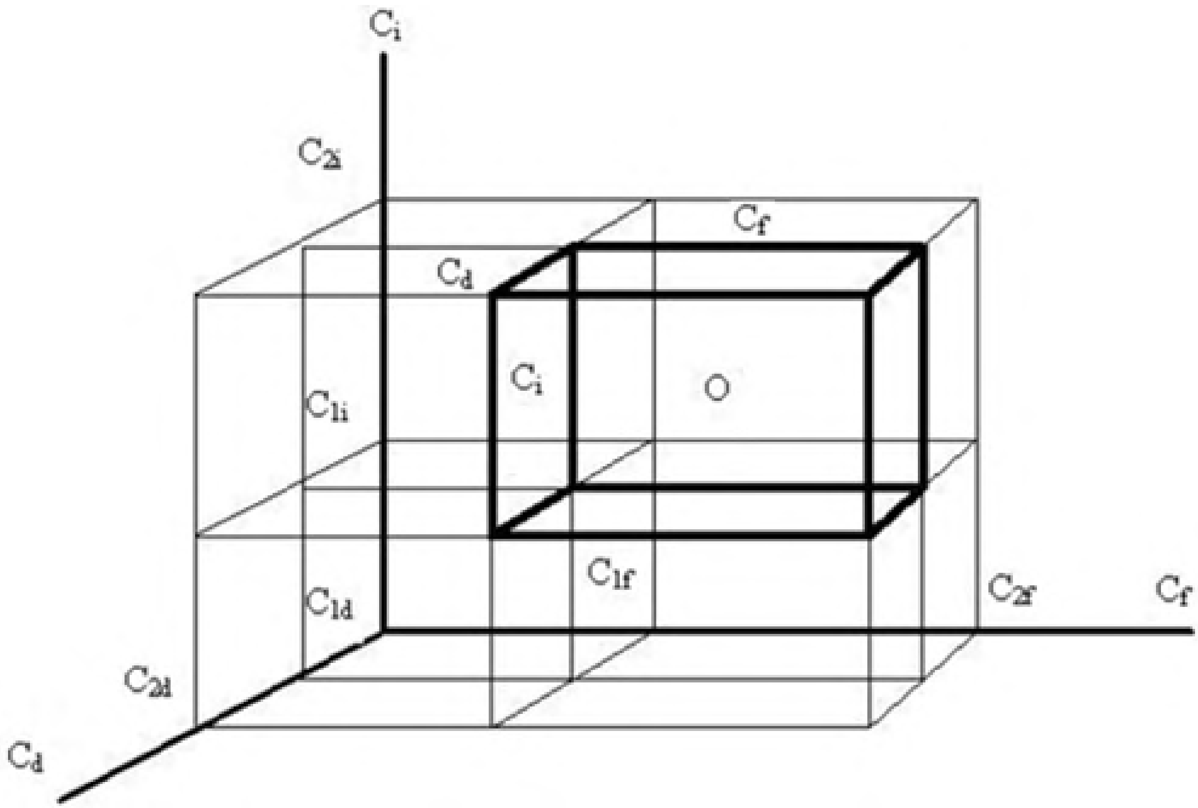

Figure 4. Spatial model of ESS with a system for regulating its ecological factors C_d, C_i, C_f in a three-dimensional coordinate system.

By substituting the corresponding vector values from expressions (4) into expression (5), we obtain the following expression:

$$\Delta = -C_{2i} \cdot C_{2d} \cdot C_{2f}. \tag{6}$$

The spatial domain of a parallelepiped can be determined using the triple integral:

$$O = \int_{C_{1i}}^{C_{2i}} dC_i \cdot \int_{C_{1d}}^{C_{2d}} dC_d \cdot \int_{C_{1f}}^{C_{2f}} f(C_i, C_d, C_d) dT \tag{7}$$

Minimization of the regulation process will be determined by minimizing the deficit of expenditures to ensure the environmental safety of the societal unit (including minimizing ΔC) while meeting the requirements for minimizing environmental hazards (ΔC) after regulating factors in the work sphere, which is determined by the deviation of indicators from the normative value (C_N).

However, the model includes only three factors C_i, C_d, C_f, while in real conditions there are many more of them, and therefore it is necessary to introduce C_j – radiation, waste, noise pollution; C_s – human potential, and others. Introducing these factors requires a transition to a four-dimensional and five-dimensional space. The transition to a four-dimensional space necessitates the construction of a four-dimensional object. Solving the minimization task in four-dimensional space can be done using linear programming.

Minimizing environmental hazards when applying regulation systems for ESS factors in the geographical space of airports will be determined by the following dependence:

$$f(O) \to -O_0 \qquad \text{at} \qquad O \to -O_{\min} \tag{8}$$

That is, the problem of determining the function $y = f(O)$ appears, which has as its limit the number O_0 at O, which goes to $O_{\min}$ for small $\varepsilon > 0$, at which one can find such a number $\delta > 0$ that corresponds to the definition I of the limit of the function. Then:

$$\mid f(O) - O_0 \mid < \varepsilon, \tag{9}$$

once:

$$\mid O - O_{\min} \mid < \delta. \tag{10}$$

This can be written in the following expression:

$$\lim f(O) = O_0 \qquad \text{at} \qquad O \to -O_{\min} \tag{11}$$

When analyzing specific models of ESS factor regulation processes for a three-dimensional coordinate system, it is necessary to determine the values of ε, δ and χ. Expert assessment of these indicators will be the criterion for minimizing the mathematical model of ESS. During the study, the main points that determine the deviations ε, δ and χ can be selected averaged indicators, which are determined by the following expressions:

for C_i:

$$C_{0i} = \frac{C_{2i} - C_{1i}}{2} \tag{12}$$

for C_d:

$$C_{0d} = \frac{C_{2d} - C_{1d}}{2} \tag{13}$$

for C_f:

$$C_{0f} = \frac{C_{2f} - C_{1f}}{2} \tag{14}$$

Thus, you can write:

$$C_{1i} + \varepsilon < C_{0i} < C_{2i} - \varepsilon, \tag{15}$$

$$C_{1d} + \delta < C_{0d} < C_{2d} - \delta, \tag{16}$$

$$C_{1f} + \chi < C_{0f} < C_{2f} - \chi, \tag{17}$$

$$\text{at } \varepsilon, \delta \quad \text{and} \quad \chi \to 0.$$

The main parameters of the spatial model of an environmentally safe space in the conditions of the studied environmental framework of the airport are determined by the existing regulations, which are reflected in the form of a 3D rectangle. By applying the base model as an ideal representation for specific living conditions of the societal unit in the environmental framework of the airport, visually, other geometric figures constructed based on real parameters will have deviations from the vector magnitude of the base model. This deviation of vectors from the real model to the base model defines the violation of normative indicators, which is a characteristic of compliance with normative requirements for environmentally safe living conditions in the investigated environment, both in static and dynamic states. A vector expression for the model of an environmentally safe space has been obtained, formalized at two levels – critically minimal (permissible) and optimal (comfortable). This approach is substantiated by ecological laws of minimum and the law of “stability” regarding existing microclimate parameters in the environmental framework of the airport.

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5. Conclusions

Post-war reconstruction of Ukrainian airports should adhere to international agreements and conventions, taking into account that modern, environmentally safe airports aim to minimize aviation's adverse effects on nature and society (employees, passengers, local residents). Emphasis on ecological safety principles will help mitigate aviation's negative impact on health and the environment. Creating ecologically safe airport space includes: adhering to environmental standards in airport development to preserve and restore local biodiversity; incorporating green spaces, eco-friendly materials, and natural ecosystems; using innovative technologies to reduce environmental impact.

Airports can be considered as integrated socio-technical systems with technical, technological, economic, social, and ecological components. Airport infrastructure, aviation technologies, social factors, as well as financial aspects are crucial components in airport systems. The safety of the airport's ecological space depends on maintaining a balance between ensuring the functionality of the ecological framework's architecture and neutralizing all forms of negative airport activities on the environment.

The development of the ecologically safe space model is based on the mathematical model of societal unit activity within the ecological framework of the airport. The model addresses questions related to minimizing negative environmental impacts. The model focuses on three main factors: assimilation potential, potential assessment, and consumption volume of "dirty resources". Real conditions may involve more factors, necessitating an extension to four-dimensional and five-dimensional spaces. Model involves reducing deficit costs while meeting requirements for minimizing environmental risks. The deviation of vectors from the real model to the base model defines the violation of normative indicators, which is a characteristic of compliance with normative requirements for environmentally safe living conditions in the investigated environment, both in static and dynamic states. The model is based on ecological laws of minimum and the law of "stability" regarding existing microclimate parameters in the environmental framework of the airport.

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Harmful emissions of welding aerosol during pulse-arc welding of structural aluminum alloy D16

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Harmful emissions of welding aerosol during pulse-arc welding of structural aluminum alloy D16

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Abstract. The results of investigations of chemical composition and emission rates of the welding fume (WF), generated during pulse-arc welding of D16 aluminum alloy with ER4043 and 2319 solid-section wires, are presented. It was established that when welding with ER4043 and 2319 wires, such harmful components as aluminum, iron and silicon are present in the WF. It was established that when using ER4043 and 2319 wires, welding fume equally belong to the least harmful "5" class of toxicity and differ in the level of emissions, which varied depending on the welding mode from class "a" to class "b" (in accordance with DSTU ISO 15011). When using ER4043 wire, the level of emissions increases with increasing values of the characteristics of the welding mode. When using wire 2319, the maximum values of the aerosol emission level are at a frequency of 100 Hz.

1. Introduction

Popular metals used on an industrial scale include aluminum. This is due to the excellent resistance of aluminum to negative external influences, good thermal and electrical conductivity. Welding of aluminium through his physical and chemical properties has the features and differences comparatively with steel and other metals and requires the high culture of production [1].

The implementation of measures to improve the working conditions of welding production workers is based on the analysis of data on the chemical composition, emission levels and toxicity of welding fumes. For this, a primary sanitary and hygienic assessment of welding materials is carried out by the method of trapping WF and determining their quantity and chemical composition.

Analysis of existing information on harmful and dangerous factors that occur during arc welding and surfacing of aluminum and its alloys has shown that this area is poorly researched, information on welding fume emissions is very limited, and there is no generalized data.

The purpose of the work is to carry out a sanitary and hygienic assessment of the nature of aerosol emissions during pulse-arc welding of structural aluminum alloy D16

2. Features of welding aluminum and its alloy

An aluminium and his alloys have a considerable sense to superficial oxidization on air, that is why their welding is conducted in the environment of protective gases, inert argon or helium, and their mixtures [2]. The presence of an oxide film increases the complexity of the process of welding aluminum structures, since the melting temperature of aluminum oxide Al_2O_3 is 2015 °C, and the melting temperature of the base metal Al is 650 °C. It follows that at the melting temperature of the surface oxide film, the aluminum under it will already boil and evaporate, so this makes the process of forming a welded joint as such impossible. Another important factor when welding this material is its high thermal conductivity, it is almost 5 times higher than that of steel, which means that in order to melt aluminum and its alloys, a much larger amount of heat must be applied and it must be applied in a highly concentrated manner [3]. To form a high-quality weld when welding aluminum alloys, non-fusible (TIG) and fusible electrode (MIG) welding methods in an inert gas environment are more often used [4]. It is for these methods that specialized powerful welding power sources and corresponding technological processes were developed, which ensure the destruction of the oxide film by a highly concentrated welding arc [5]. Pulse welding power sources are also widely used for aluminum welding, which use the principle of simultaneous combination during welding of the main working welding current and pulse current of adjustable frequency, which has a higher peak value. Due to it, the efficiency of the welding arc and the quality of the transfer of the electrode metal are significantly increased, and the destruction of the oxide film is improved. It also allows you to reduce overheating of the metal, which significantly improves the physical and mechanical qualities of welded joints [6].

3. Normative requirements for air in the working area

Due to the increase in requirements for the quality of the welding seam, welding processes are constantly being improved [7]. In addition, the sanitary and hygienic requirements for welding materials are increasing. Despite the increasing mechanization and automation of welding operations, the role of the welder, as an active and main link in the execution and control of the welding process, will remain decisive for a long time. The creation of workplaces, welding equipment and working conditions that meet the specified requirements allows the welder to perform work movements and control the welding process with high accuracy and reliability under optimal physical stress and nervous tension, maintaining high efficiency during the entire shift. Neutralization of welding fumes is necessary to improve working conditions [8]. For this, data on the chemical composition and emission levels of WF are required. This will make it possible to choose means of local ventilation or more ecological welding materials.

Numerous studies show that accumulating in the body, aluminum:

- acts on brain cells;
- causes anemia, arthritis;
- suppresses the production of gastric and salivary enzymes;
- contributes to the development of osteoporosis and rickets.

A welder can get sick with irreversible aluminosis – pathological changes in the lungs that develop when inhaling aluminum dust [9].

In accordance with the international standard ISO 14000, welding materials are subjected to new requirements for their continuous improvement in order to minimize the harmful effects on the human body, and according to the standards of DSTU ISO 15011 [10], welding materials must be constantly monitored for occupational safety indicators (chemical composition, emission level, toxicity and hygienic class of welding aerosols).

In the countries of the world, sanitary services control harmful substances in the air of the working area of industrial premises. For this, regulatory requirements are used that determine the maximum allowable concentrations (MAC) [11]. These are such concentrations that during daily work do not cause occupational diseases in workers. Their value is regulated by special sanitary regulations, which include data on the maximum concentration of harmful gases and aerosols near the welder's workplace (at breathing level), which is not harmful to health during an eight-hour working day. According to the hygienic regulations of chemicals in the air of the working area, the maximum permissible concentration of aluminum and its alloys in the air of the working area is 2 mg/m^3 and belongs to the 3rd class of danger [12]. The MPC value for neutral dust that does not have poisonous properties is 10 mg/m^3.

4. Processes of welding fume generation during MIG and MAG welding of aluminum and its alloy

A schematic view of the formation process of WF during mechanized welding of non-ferrous metals in a shielding gas environment is shown in figure 1.

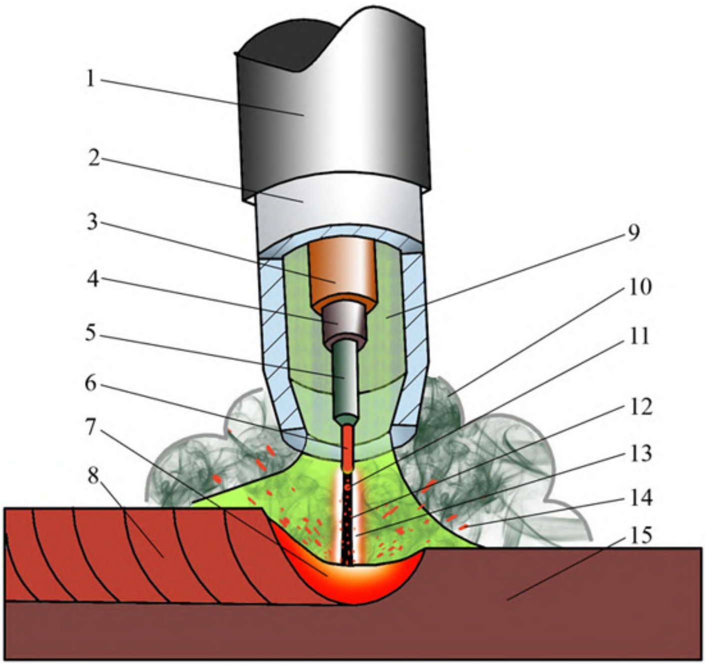

Figure 1. Formation of welding fume during MIG and MAG welding: 1 – torch; 2 – gas nozzle; 3 – insulator; 4 – tip adapter; 5 – contact tip; 6 – welding wire; 7 – welding pool; 8 – weld; 9 – shielding gas; 10 – gases and welding fume; 11 – a drop of molten wire; 12 – arc column; 13 – arc flame; 14 – sparks (splashes) of liquid metal; 15 – base metal.

Under the action of the heat of the arc, a drop of liquid metal is formed and grows on the end of the wire, which is held by the forces of surface tension. Partial evaporation of the metal occurs, as a result of the high boiling temperature of the metal and significant heat of evaporation. Passing through the protective gas supplied to the welding zone, part of the metal vapor condenses into droplets, oxidizes and turns into small solid particles of metal oxides, which form a fume and always surround the welding arc.

5. Procedure of experiments

The scheme of the stand for sampling WF during mechanized welding with aluminum wires in the environment of protective gases is shown in figure 2.

Sampling of WF for their dissolution is carried out in accordance with the standard applying the method of complete capture of the fume, generated during welding with the use of the special bench with the FPP filter installed on a way of movement of WF from a shelter of a welding zone. The following indices of WF formation were determined: intensity of Va emission, g/min; chemical composition of WF, wt.% For each variant at least three experiments were performed.

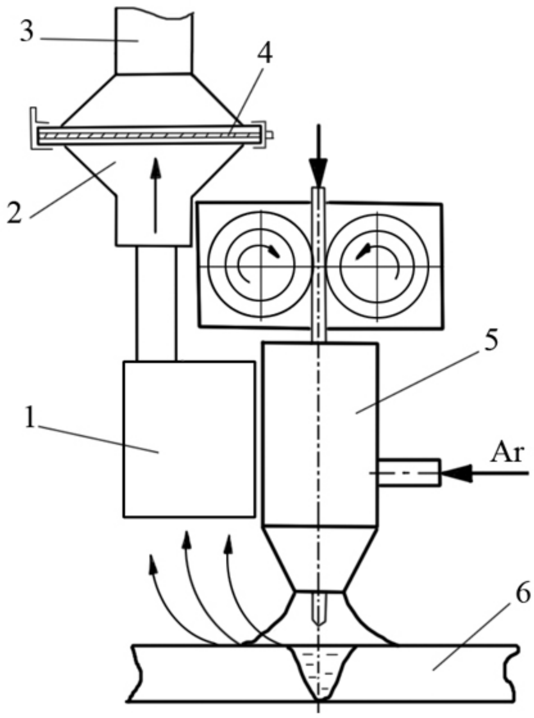

Figure 2. Scheme of the stand for sampling WF during MIG welding with solid wires: 1 – catching nozzle (covering the welding zone); 2 – filter holder chamber (measuring and distribution chamber); 3 – nozzle to the aspirator; 4 – filter for chemical analysis; 5 – burner; 6 – metal to be welded.

The following two indicators are used to determine the final indicators of the hygienic assessment of welding materials by the calculation method in accordance with the DSTU ISO 15011-4:2008 standard:

1. Limit value of welding fume as a measure of toxicity ($LV_{WF(A)}$)
2. Class of welding fume, indicator of the risk of exposure to WF on the human body at a specific workplace.

After the chemical analysis, the obtained results are evaluated.

6. Choice of material and results of investigations

At the E. O. Paton Electric Welding Institute of the NAS of Ukraine conducted a study of the chemical composition, emission levels and toxicity of aerosols formed during mechanized welding of aluminum-based alloys using methodological standards of the ISO 15011 series. To conduct the research, the pulse-arc method of welding D16 aluminum alloy was chosen. Welding was performed with two brands of solid wire ER-4043 and wire 2319 with a diameter of 1.6 mm, which are serial and certified and widely used in industry. The thickness of the D16 plate is 4 mm. The chemical composition of the welding materials used is shown in table 1. The MIG welding process was carried out using an A1431 welding machine and a pulsed power source with a built-in algorithm for regulating the shape of a specialized multi-level current pulse, developed at the E. O. Paton Electric Welding Institute of the NAS of Ukraine for pulse-arc welding with a fusible electrode in shielding gases. Welding was performed with a direct current of reverse polarity with a pulsed current of a set frequency superimposed on it. Argon was used as a shielding gas. Gas consumption (Ar) was 20-25 l/min. The set welding speed is 25 m/h. The current of the welding mode I_{w1}, I_{w2}, I_{w3} indicated the average values of the sum of direct current and pulsed current that flow simultaneously in the welding arc.

Table 1. Chemical composition of plate D16, wires of solid section 2319 and ER4043.

Brand	Chemical composition, wt. %									
	Si	Fe	Cu	Mn	Mg	V	Ni	Zn	Ti	Al
D16T	0.5	0.5	3.8-4.9	0.3-0.9	1.2-1.8	–	0.1	0.3	0.1	the rest
2319	0.2	≤ 0.3	5.6-6.8	0.2-0.4	0.02	0.05-0.15	–	0.1	0.1-0.2	the rest
ER4043	4.5-5.5	≤ 0.8	≤ 0.3	≤ 0.05	–	–	–	–	≤ 0.2	the rest

The welding modes used in pulse-arc welding of D16 aluminum alloy with ER4043 and 2319 solid-section wires are listed in table 2.

Table 2. Welding modes during the research.

Grade of wire:	ER4043			2319		
parameters	Regime 1	Regime 2	Regime 3	Regime 1	Regime 2	Regime 3
f, Hz	70	100	130	70	100	130
I_w, A	120	160	180	110	160	180
U_w, V	20	22	24	22	22	24
V_{feed}, m/min	2.82	4.08	5.1	2.82	4.08	5.1
g, kg/min	0.015333	0.022167	0.027667	0.015333	0.022167	0.027667

The results of the study of the intensity of welding fume emissions during pulse-arc welding of D16 aluminum alloy with ER4043 and 2319 solid-section wires are shown in figure 3.

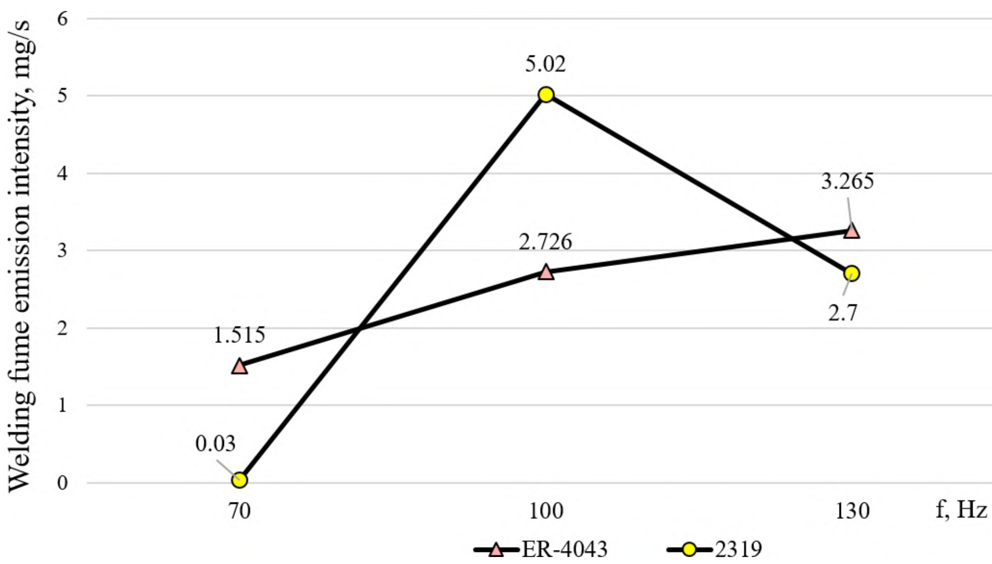

Figure 3. Intensity of welding fume emission during MIG welding with ER-4043 and 2319 aluminum wires with a diameter of 1.6 mm.

As we can see, the intensity of welding fume emissions during MIG welding with ER-4043 aluminum wires is directly dependent on the frequency of the pulsed current superimposed on the main direct current of reverse polarity. Thus, with increasing frequency, the intensity of WF emissions increases. Gross welding fume emissions during MIG welding with 2319 aluminum wire do not have a direct dependence on pulse frequency. The lowest emission values were recorded at the experimental pulse frequency of 70 Hz, and the highest values at the frequency of 100 Hz.

The results of the study of the chemical composition of welding fumes during pulse-arc welding of D16 aluminum alloy with ER4043 and 2319 solid-section wires are shown in table 3.

Table 3. Mass fraction of chemical elements in the welding fume.

Grade of wire	Mass fraction in WF, %			
	Al	Si	Mn	Fe
ER-4043	2.33	1.81	0.127	18.3
2319	2.274	1.4	Not found	19.5

For clarity, graphs of the emission intensity of the i-th component at different welding modes were constructed (figure 4).

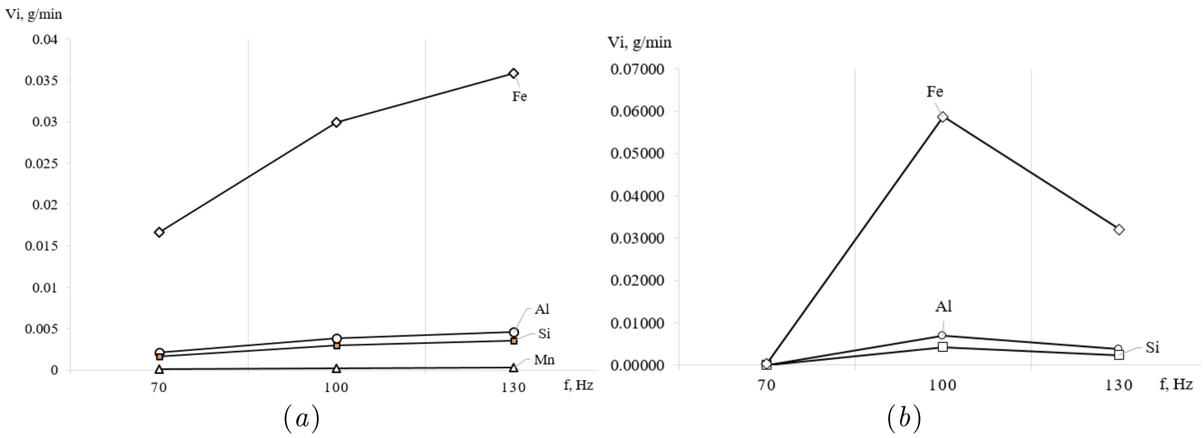

Figure 4. Comparative graph of the intensity of formation of elements in the WF composition during MIG welding with aluminum wire: (a) ER-4043 and (b) 2319.

As we can see, a larger mass of toxic elements in the welding fume during MIG welding with aluminum wires ER-4043 and 2319 consists of such components as aluminum, iron and silicon. The emission intensity of these welding fume components increases with increasing pulse frequency.

To determine the final estimated indices of hygienic evaluation of welding materials in compliance with the standard DSTU ISO 15011-4: 2008, the limit value of the welding fume was determined by the following equation:

$$LV_{WF(A)} = \frac{100}{\sum_{1}^{n} \frac{i}{LV_i} + \frac{100-\sum_{1}^{n} i}{LV_{WF}}}$$

where $LV_{WF(A)}$ is the total limit value of the welding fume, in mg/m^3; n is the number of main components of the welding fume; i is the fraction of i-th main component of the welding fume in %; LV_i is the limit value (MAC) in mg/m^3 for i-th main component of the welding fume; LV_{WF} is the limit value in mg/m^3 for the welding fume, which contains chemicals with a low and medium toxicity, if such a limit was established, or a limit value in mg/m^3 for inhaled dust, if no limit value for the welding fume was established.

Due to the fact that the procedure does not allow determining the content of all components of WF to bring its composition to 100 %, it was assumed that in addition to the revealed components, the residue of WF represents a non-toxic dust with MAC of 10 mg/m^3. The results of the calculation are shown in table 4.

To calculate the toxicity, the data of MAC of toxic components were used in accordance with the hygienic regulations of chemicals in the air of the working area [12].

Table 4. Indices of hygienic evaluation of welding materials determined by the calculation method in accordance with the standard DSTU ISO 15011-4:2008.

Grade of wire	Welding mode	Va, mg/s	$LV_{WF(A)}$, mg/m^3	Category of electrode
ER-4043	Regime 1	1.515	7.665	5a
	Regime 2	2.726	7.665	5a
	Regime 3	3.265	7.665	5b
2319	Regime 1	0.03	8.052	5a
	Regime 2	5.02	8.052	5b
	Regime 3	2.7	8.052	5a

According to the limit value of the welding aerosol, these wires belong equally to the fifth class (“5”), their calculated toxicity values have a slight difference (for wire ER-4043 – $LV_{WF(A)}$ is equal to 8.456 mg/m^3; for wire 2319 – $LV_{WF(A)}$ is equal to 8.993 mg/m^3). According to the DSTU ISO 15011-4:2008 classification, class “5” has the highest MAC values, that is, it is the least harmful. As for the level of welding fume emission, it varies depending on the welding mode and its class varies from “a” to “b”, according to the standard, this designation corresponds to the lowest emission of aerosol mg/s. The highest values of WF intensity were recorded when welding with 2319 wires at a frequency of 100 Hz.

7. Conclusions

In order to ensure the maximum improvement of the hygienic characteristics of the air in the working area, it is necessary to choose the optimal combination of the following technological methods of reducing the level of emissions of harmful substances:

1. Welding materials should be selected according to the classification of DSTU ISO 15011-4:2008, where the limit value of WF (mg/m^3) varies from the most toxic “0” to the least toxic “5”, and the level of emissions (mg/s) is its small values from “a”, and high to “e”.
2. When choosing wires taking into account hygienic characteristics during pulse-arc welding of structural aluminum alloy D16, pay attention to the level of emissions that change depending on the welding mode. Since ER-4043 and 2319 wires equally belong to the “5” class according to the limit value of WF (mg/m^3)
3. The obtained results of the carried out investigations can be used during calculation of the systems for mechanical ventilation: determination of amount of air L (m^3/h) which needs to be supplied or removed from the room. To calculate the ventilation of production

rooms where welding is used, air exchange is required, which is usually determined by the calculation method based on specified data on the amount of harmful substances emissions.

The obtained results are necessary for improving the working conditions of welders and workers in production facilities, which will contribute to reducing of occupational diseases. Work allows you to protect the environment from harmful substances

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Air pollution forecasting by leveraging traffic modeling techniques

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Air pollution forecasting by leveraging traffic modeling techniques

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Abstract. Forecasting of short-term air pollution caused by nitrogen dioxide is valuable for decision making about human health protection. Open real world data collected in Madrid over a period from 2019 to 2022 were used. Trends and patterns in air pollution are presented and analysed. Causation between air pollution by nitrogen dioxide and traffic is investigated. Results of traffic forecasting obtained by corresponding bidirectional Long Short-Term Memory (LSTM) models at the selected stations as well as values of nitrogen dioxide concentration over historic horizon of 6 hours at the same station are used for forecasting of air pollution by nitrogen dioxide as features for LSTM models. Models were created and trained for each air pollution measurement station presented in the corresponding dataset. Forecasting is made for 6 hours ahead. The study confirmed that traffic forecasting results are valuable for models of forecasting air pollution by nitrogen dioxide. It provided increase in forecasting accuracy in comparison with the usage of historical values of traffic as input features. The obtained results improved MAE by 5 % and MSE by 6.37 % comparing to LSTM models with only previous values of air pollution by nitrogen dioxide. It defines an important approach which should be applied for more complex architectures of deep learning models in the following investigations.

1. Introduction

Air pollution has significant negative impact on human health. There are different air pollutants with a main set containing particulate matters (PM2.5 and PM10), nitrogen dioxide, ozone, sulfur dioxide, carbon monoxide.

Nitrogen dioxide is one of the main air pollutants regarding impact on human health particularly in the developed countries. World Health Organization defines recommended levels of nitrogen dioxide. Guidelines [1] contain two indicators:

- long-term (annual) average level set at 25 $\mu g/m^3$;
- short-term (over 24 hours) average level set at 10 $\mu g/m^3$.

Therefore, appropriate decision making about air pollution requires long-term and short-term forecasting models of air pollution caused by nitrogen dioxide. This study is aimed at short-term forecasting of concentration of nitrogen dioxide. Decisions in short term require accurate forecasting, being more sensitive for changes in concentration of nitrogen dioxide. It is known, that not only architecture of forecasting models impacts on accuracy of obtained results, but input feature set as well. At the same time one of the main causes of nitrogen dioxide is traffic. Vehicle emissions increase concentration of nitrogen dioxide in the air. As well as concentration of nitrogen dioxide, traffic does not have static values. So the question is, what period of traffic values should be used in forecasting models?

There is a range of investigations on air pollution, in particular [2–14]. Ivanova et al. [2] apply simple Auto-Regressive Integrated Moving Average model for investigation of nitrogen dioxide concentration. It is followed by seasonal version of this model in the paper by Molina-Cueva et al. [3]. But these models are used for middle or long-term predictions. Time series regression models were developed by Neykov et al. [4]. Li et al. [5] investigates Long Short-Term Memory (LSTM) models for nitrogen dioxide concentration forecasting which are prior to back propagation neural network in terms of forecast accuracy. In the paper by Kristiani et al. [6] LSTM model was proposed to forecast PM2.5 concentration, and the investigation [7] used its aggregated version based on data from different stations. LSTM models had more accurate results compared to support vector machine based regression, gradient boosted tree regression. In the paper by Ding et al. [8] LSTM models were applied for Air Quality Index forecasting with better results as to convolutional neural networks. Papers [9, 10] use LSTM models as well, and papers [11, 12] proposed advanced versions of LSTM.

In the papers [9–11, 13, 14] values of traffic are used as additional input features for forecasting. But in general review of the literature revealed that traffic is fed into existing forecasting models only by its previous values. Some time horizon is used to measure concentration of nitrogen dioxide in the air and traditionally traffic at the place where pollution is measured. This time horizon is a historical one. As short-term forecast is considered, time horizon is defined by a number of hours. Then the measured values are fed into a model to forecast concentration of nitrogen dioxide for the next hours. The next hours are defined as a forecast horizon.

This investigation is an attempt to use values of traffic on forecast horizon instead of historic time horizon as input features for forecasting models. It is necessary to check if it makes forecasting models more accurate.

2. Methodology

Taking into account the results of analysis presented in the first section, different deep learning models should be created. But these models should have the same architecture to investigate impact of traffic on the results of air pollution forecasting. This architecture is presented by LSTM in the paper. It has been chosen because of its wide application for air pollution forecasting in particular and for forecasting in general. The results of studies [2, 5–14] were taken into account as well.

As the problem of forecasting air pollution by nitrogen dioxide is a problem of time series forecasting, it is obvious that values presenting concentration of nitrogen dioxide should be measured on historic time horizon and used as input features for a forecasting model. If a set of measurement stations is given, then a separate model should be created and trained for each station. Each station is defined to measure concentration of nitrogen dioxide in the air at a certain place.

The problem of forecasting air pollution by nitrogen dioxide was considered under constraints. Such an approach allows to apply the proposed models for the cases when a system of measurement stations of traffic and air pollutants does not cover all corresponding city structure. Traffic and air pollution by nitrogen dioxide can be measured at different places. This approach not only creates the possibility, but defines an issue as well. Because different stations at different places can be used to measure traffic and air pollution, it is necessary to define a way to get input features presenting traffic for a forecasting model. In this study it was proposed to use feature selection method based on decision tree ensembles created by Random Forest method. It allows to get the most appropriate traffic measurement stations for each air pollution measurement station. The main idea is to select a subset of traffic measurement stations with the biggest impact on concentration of nitrogen dioxide at certain station based on the historic dataset.

When a subset of traffic measurement stations is selected, corresponding values of traffic should be used as input features for a forecasting model. In this paper it is proposed to use these values on forecast horizon. As values of traffic on forecast horizon are not known for sure at the moment of forecasting air pollution, method for traffic forecasting should be applied. It is proposed to use the method [15], as it is applicable under the constraints defined above. This method creates a bidirectional LSTM model with input features presenting traffic values on historic horizon at forecast station and selected stations as well.

As a result air pollution forecasting model with LSTM architecture is created for a station, using the following input features:

- values of nitrogen dioxide concentration over historic horizon of length H at the same station: $p(0), p(1), \dots, p(H-1)$ for sequential hours with numbers $0, 1, \dots, H$;
- values of traffic, forecasted over a corresponding horizon at the Q selected traffic measurement stations: $t(st(i), H), t(st(i), H+1), \dots, t(st(i), 2H)$ for sequential hours at the i-th selected measurement station with number $st(i)$, where $i = \overline{0, Q-1}$.

So every input data sample is a vector $x^0 =< p(0), p(1), \dots, p(H-1), t(st(i), H), t(st(i), H+1), \dots, t(st(i), 2H) >$, where $i = \overline{0, Q-1}$.

Every i-th LSTM cell consists of state unit s_i^t, forget f_i^t, external input g_i^t and output q_i^t gates for time step t. Biases b_i^f, input weights U_i^f, recurrent weights W_i^f should be defined for forget gates and other gates accordingly. Input vector is defined as x^t. The following computations are used [16]:

$$f_i^t = \sigma(b_i^f + \sum_j U_{i,j}^f x_j^t + \sum_j W_{i,j}^f h_j^{t-1}), \tag{1}$$

$$s_i^t = f_i^t s_i^{t-1} + g_i^t \sigma(b_i + \sum_j U_{i,j}^f x_j^t + \sum_j W_{i,j}^f h_j^{t-1}), \tag{2}$$

$$g_i^t = \sigma(b_i^g + \sum_j U_{i,j}^g x_j^t + \sum_j W_{i,j}^g h_j^{t-1}), \tag{3}$$

$$h_i^t = tanh(s_i^t) q_i^t, \tag{4}$$

$$q_i^t = \sigma(b_i^o + \sum_j U_{i,j}^o x_j^t + \sum_j W_{i,j}^o h_j^{t-1}). \tag{5}$$

3. Results

Experimental investigation was conducted to check if the proposed approach applicable. Real world data were used. The data were collected in Madrid over a period from 1.01.2019 until 30.09.2022 and presented in open access at Open data portal of Madrid City Council [17]. As the proposed methodology includes values of air pollution by nitrogen dioxide and traffic as well, corresponding data presenting nitrogen dioxide concentration [18, 19] at stations [20] and traffic values [21] were used.

At first the data were studied to reveal its structure. Hourly levels of air pollution by nitrogen dioxide at 3 different stations in Madrid over the periods of three days are presented in figure 1 for stations Parque Juan Carlos I, Parque del Retiro, Casa de Campo and in figure 2 for stations El Pardo, Ensanche de Vallecas, Plaza Eliptica. These figures display some time patterns for dynamics of air pollution by nitrogen dioxide. But at the same time these patterns are not static and certain values for different stations could be closer to each other (figure 1) or more distant (figure 2).

Patterns presented in figure 3 display that concentration of nitrogen dioxide at the same station is varied through days and hours. Part (a) of figure 3 presents different days marked

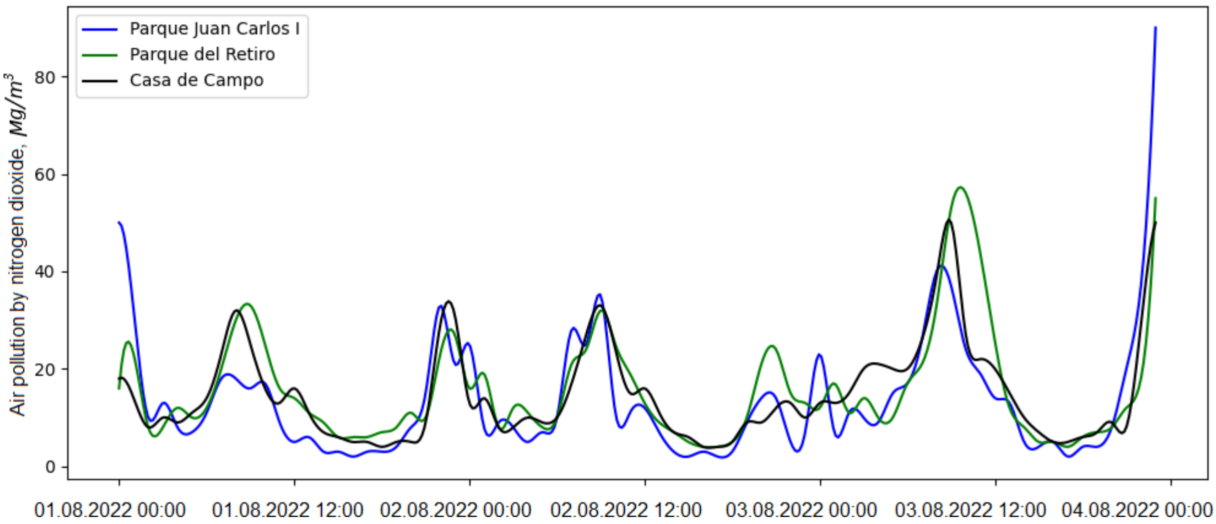


Figure 1. Hourly levels of air pollution by nitrogen dioxide at 3 measurement stations over the period 1-3.08.2022.

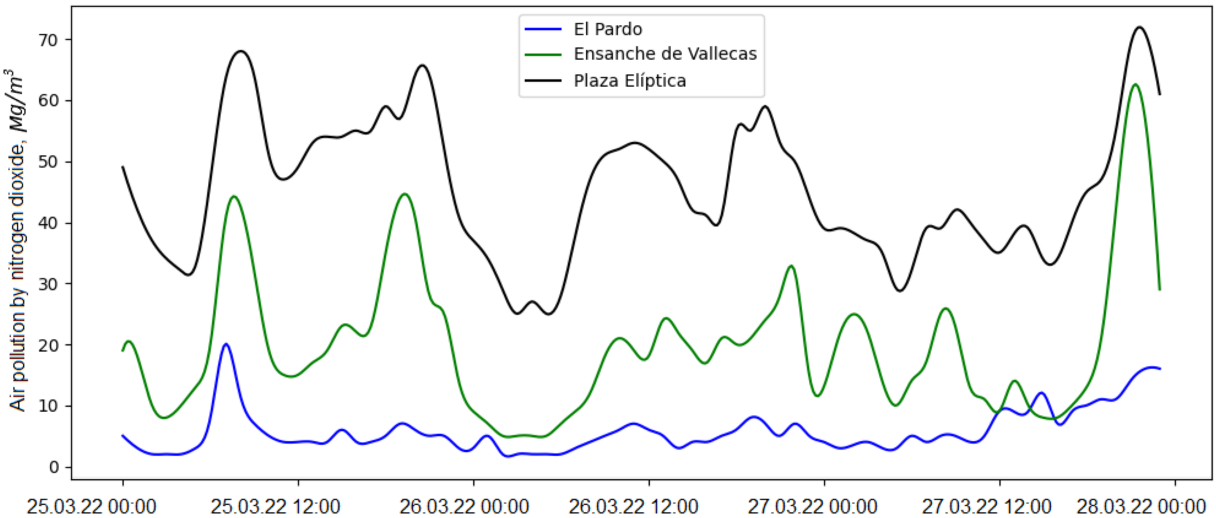
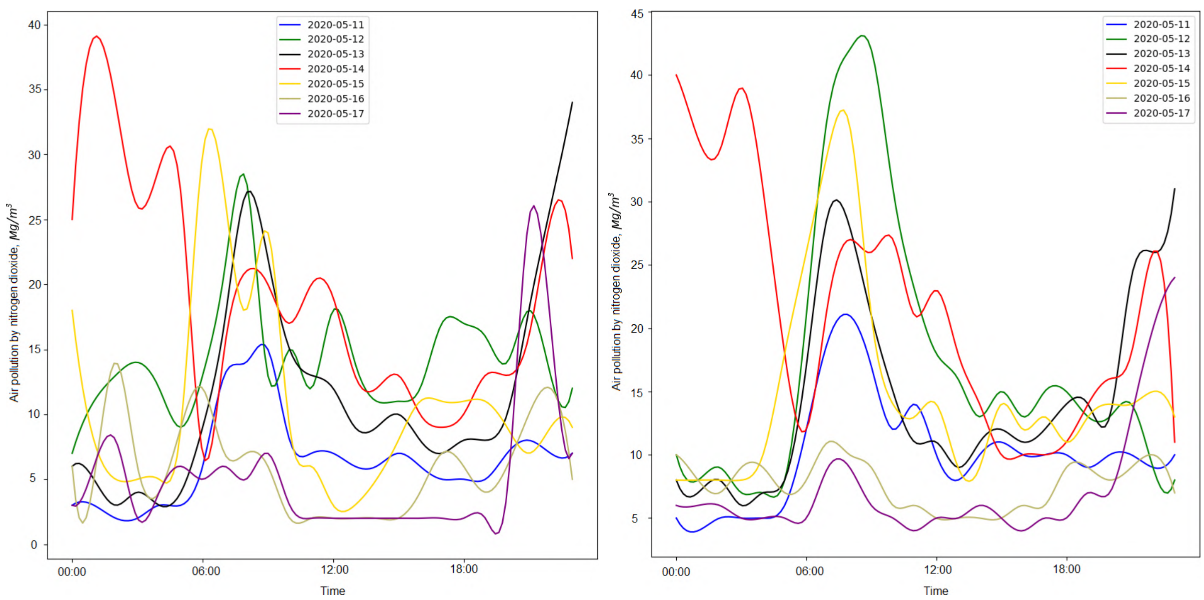


Figure 2. Hourly levels of air pollution by nitrogen dioxide at 3 measurement stations over the period 25-27.03.2022.

with corresponding colors for Barajas station and part (b) for Villaverde Alto. It clearly shows that concentration of nitrogen dioxide is lower at the weekend, but it is obviously not static through working days as well. At the same time surges of concentration are possible at night (on May 14th, 2020 at both stations), despite general trend for lower values at night.

The figure 4 contains average values of air pollution by nitrogen dioxide at a measurement station for a month. Each part of figure 4 presents a year from 2019 to 2022 and has marks for each month of a year. Different colors at every month mark present corresponding stations (Casa de Campo, Barajas, Vallecas). Annual trends of air pollution by nitrogen dioxide are varied through different measurement stations (figure 4). But at the same time there is a pattern of pollution reduce over a period from March to September. Average monthly values are higher at the beginning of the year and in the end as well. There is a clear trend toward lower concentration of nitrogen dioxide through 2020 when the COVID-19 pandemic happened.



(a) (b)

Figure 3. Hourly levels of air pollution by nitrogen dioxide at the same station (Barajas (a) and Villaverde Alto (b)) during a week.

Every sample has a mark representing verified or non-verified (wrong) value. The data were checked using this information to exclude inappropriate values. Then the data were processed to represent a time series with historic and forecast horizons equal to $H = 6$ hours. Interpolation was used to represent non-verified values. Two datasets representing correspondingly air pollution and traffic as outputs were created.

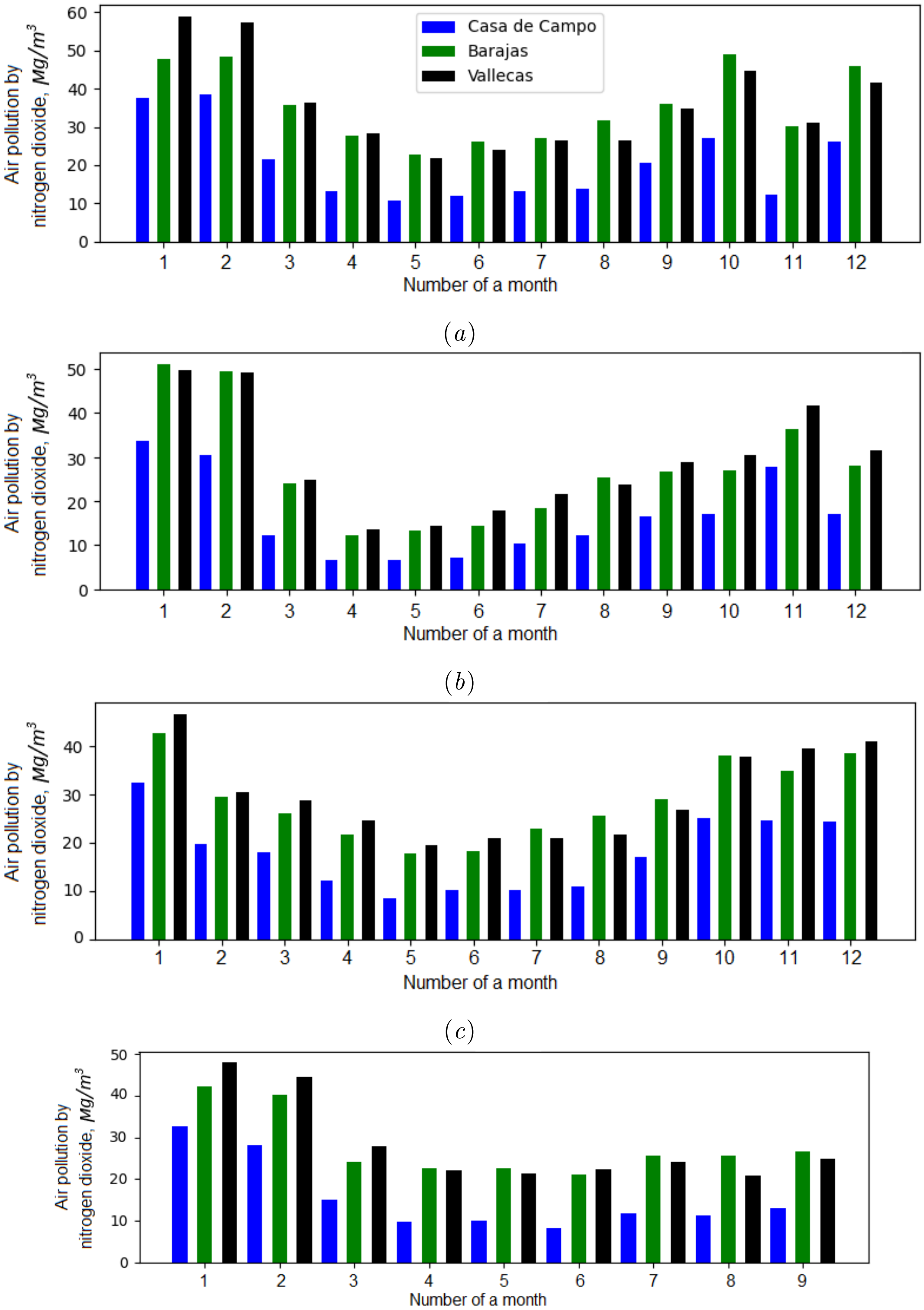
Experimental investigation was conducted on the presented datasets. Datasets were divided appropriately: 60 % for training, 20 % for validation and 20 % for testing. LSTM models were created and trained for all 24 stations separately. Besides models based on the proposed methodology, two other variants of LSTM models were created:

- with values of air pollution by nitrogen dioxide for 6 previous hours (base models);
- with values of air pollution by nitrogen dioxide for 6 previous hours and traffic for the same previous hours (alternative models).

Two indicators were used for evaluation of results: mean absolute error (MAE) and mean squared error (MSE). As MAE and MSE were calculated for 24 stations individually, final results in table 1 present average obtained values.

Base and alternative models were created as LSTM models with 3 layers of LSTM cells. Each layer has 12 cells. This structure demonstrated the best results. The last layer is a dense one. Adam optimization algorithm was used. Mean squared error was applied as a loss function. Proposed models are differed by its structure: 2 layers with 12 cells in each one. Number of selected traffic measurement stations $Q = 2$.

Experimental results (table 1) demonstrate that the proposed model reduced MAE from 0.04812 to 0.04571 and MSE from 0.00518 to 0.00485. It improved base MAE by 5 %. The proposed approach has the best results with lower levels of both MAE and MSE in comparison with the usage of previous values of traffic as additional input features. On average, the proposed approach improved base MSE (LSTM with only previous values of air pollution) by 6.37 %, which is higher than 1.35 % of alternative model.



(a) (b) (c) (d)

Figure 4. Air pollution by nitrogen dioxide through 2019(a), 2020(b), 2021(c), 2022(d).

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Table 1. Experimental results of forecasting air pollution by nitrogen dioxide using LSTM models with different input features.

LSTM model characteristics	MAE	MSE
Previous values of air pollution by nitrogen dioxide	0.04812	0.00518
Previous values of traffic and previous values of air pollution by nitrogen dioxide	0.04668	0.00511
Forecasted values of traffic and previous values of air pollution by nitrogen dioxide	0.04571	0.00485

4. Conclusions

Forecasting of air pollution is a well known scientific problem. The same is true for traffic forecasting. Air pollution by nitrogen dioxide is connected to traffic activity in urban environments, but only some existing papers consider traffic values as additional features for air pollution forecasting. That is why forecasting of air pollution caused by nitrogen dioxide was investigated in the paper emphasizing the role of traffic data. But new approach was proposed. The idea is to apply results of traffic modeling techniques as inputs to forecast level of air pollution by nitrogen dioxide. These additional inputs are forecasted values instead of historic values used in the known studies.

Deep learning models based on LSTM architecture were created, trained and tested. Data collected in Madrid over a period from 2019 to 2022 were used for experimental investigation. The data were processed and transformed into an appropriate datasets.

Forecasting models with base input features for 6 previous hours were compared to the models with additional features presented by values of traffic. The proposed approach used forecasted values of traffic instead of historical values of traffic as input features. As traffic measurement stations differ from air pollution measurement stations, additional features presented values for 6 hours at selected traffic measurement stations. The selection was made using decision tree ensembles created by Random Forest method. The obtained results improved MAE by 5 % and MSE by 6.37 % on average.

The proposed approach is valuable, as it allows to increase forecast accuracy. At the same time accurate forecasts of air pollution by nitrogen dioxide are critical for decision making. As more complex architectures of deep learning models are promising for air pollution forecasting, it is necessary to apply the results of traffic modeling techniques to such architectures in the following investigations.

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Improvement in the evaluation of gamma radiation from cylindrical bodies with spatially inhomogeneous source activity distribution

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Improvement in the evaluation of gamma radiation from cylindrical bodies with spatially inhomogeneous source activity distribution

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Abstract. Radioactivity and radioactive materials are constant companions of our life. Therefore, their studies and utilization are an important part of the development of human society. One of lines of work with radioactivity of various media concerns their gamma ray spectrometry which covers the issues of mineral exploration, ecological monitoring, medicine, security, agriculture, anti-terrorist protection, assessment of the consequences of man-made and natural disasters, etc. The tasks of spectroscopy include the description, survey, and analysis of gamma fields produced by natural environment or artificial objects. To solve these tasks effectively, mathematical modeling based on the fundamental physical laws of radioactivity and modern achievements of mathematics and informatics is used. In particular, in this research, we consider the gamma radiation from the cylindrical body and develop the procedure for assessing the gamma flux intensity when the source activity is inhomogeneously distributed over the body volume. The procedure is a semi-analytic approach and is based on the representation of the source activity function as a linear combination of step functions. Physically it means the approximation of inhomogeneous body by a layered medium. The procedure also allows one to get an analytical expression for the gamma flux intensity which is observed at the axes of symmetry of the cylindrical body. It is performed the comparison of approximate and exact values of intensity for exponential source activity function when analytical integration is possible. We also discuss the procedure application to the case when the source activity function is nonmonotonic and restrictions of procedure use appear.

1. Introduction

Improvement of technologies, methods of nature management, and safety components stimulates the development of economies and human societies. New ideas and their accelerated implementation as a sign of the modern pace of life also affected the gamma spectroscopy methods [1, 2]. Work with radioactive materials that have penetrated essentially into all areas of our life demands the organization of effective control and radiation safety [3, 4]. To achieve this, it is used various tools including stationary observations [5] and remote sensing [3, 6–11], combined with information technologies, mathematical modeling, etc.

Although the introduction of modern methods of data analysis using neural networks [12] and the development of computing capabilities have significantly improved the survey of radioactive objects in all its aspects, the improvement of the description of simple objects and the comprehensive analysis of their radiation fields is still an important task that contributes to the correct understanding of the physics of processes, the development of test and calibration installations, the formation of the theoretical foundations of spectrometry, and also feeds adjacent fields of science with new challenges.

In particular, we are going to use the achievements of mathematical modeling in order to improve the description of gamma radiation field produced by the cylindrical body containing the sources of radioactivity distributed heterogeneously. This problem leads us to the evaluation of the integrals which cannot be represented via analytical expressions, therefore it is hard to conduct the parametric analysis, to apply them to inverse problems, etc. The procedure we develop allows one to get quite simple and highly accurate derivations of complicated integrals appearing in spectrometric problems.

2. Research aim and objectives

This research concerns the analytical description of gamma ray fields produced by radioactive cylindrical bodies (disks), when the disk's source activity depends on the spatial coordinate. In particular, we develop the semi-analytical procedure which is based on the representation of the source activity function via the linear combination of step functions. The results of utilizing this procedure are compared with the exactly solvable classical case when the source activity is described by an exponential function. Moreover, it is considered the nonmonotonic activity function, when the application of the procedure can be complicated.

3. Gamma ray field of a radioactive disk with inhomogeneous source activity

Among the problems accompanying the investigations of gamma field monitoring there are the cases when the structure of gamma ray radiation can be described analytically [13]. Now we are going to consider cylindrical bodies (thick disks). As is known [1], the gamma ray field produced by the homogeneous symmetric disk with constant source activity can be evaluated analytically. When the source activity function is not constant, only partial cases lead to the final analytical relations. Thus, let us develop the procedure to evaluate gamma ray fields for nonconstant source activity functions. Before we start to outline the procedure's stages, a brief theoretical background [1, 2, 14, 15] should be mentioned.

The starting point for evaluating the mono-energetic non-scattered gamma flux emitted from a point source is the following relation for the intensity I:

$$I = \frac{q}{4\pi r^2} \exp\left(-\int_0^r \mu(s)ds\right), \tag{1}$$

where q is the source activity (quants per second), r is the distance from the observation point to a source, μ is the attenuation coefficient along r.

This relation allows one to evaluate the gamma field generated by a plane source in a conventional way, integrating relation (1) over some spatial domain. For instance, when we deal with a *thin* radioactive disk of radius R, then the gamma flux intensity I evaluated at the distance h from its center obeys the following relation

$$I = \frac{q}{2}\left[E_1\left(\sum_{i=1}^{k} h_i\mu_i\right) - E_1\left(\frac{1}{\cos\alpha}\sum_{i=1}^{k} h_i\mu_i\right)\right], \tag{2}$$

where the function $E_1(x) = \int_x^\infty t^{-1}e^{-t}dt$ is exponential integral of the first kind; h_i are the thicknesses of parallel layers lying above the disk ($h = \sum_i^k h_i$); μ_i are the attenuation coefficients for the layers; $\cos\alpha = h/R$.

Here we are interested in the gamma flux of radioactive *thick* disk of radius R and thickness d (figure 1). To evaluate corresponding intensity at a distance H from the top of the disk on its vertical symmetry axis (figure 1), we use the relation (2) and integrate it over the vertical coordinate z. Thus, the general relation

$$I = \int_0^d \frac{q}{2}\left[E_1\left(\mu H + \nu(d-z)\right) - E_1\left(\frac{\mu H + \nu(d-z)}{\cos\alpha(z)}\right)\right]dz, \tag{3}$$

where ν and μ are the coefficients of attenuation for the disk material and medium beyond the disk, respectively. To simplify the theoretical studies, the quantity $\cos\alpha(z)$ is assumed to be constant, although the incorporation of this dependence can be performed with any degree of accuracy [16].

When the source activity q is constant or some elementary function of z, the relation (3) can be presented in an analytical form. For instance, when $q = q_0 = \text{const}$, from (3) it follows

$$I = \frac{q_0}{2\nu}\left[E_2\left(\mu H + \nu(d-z)\right) - \cos\alpha\, E_2\left(\frac{\mu H + \nu(d-z)}{\cos\alpha}\right)\right], \tag{4}$$

where $E_2(x) = x\int_x^\infty t^{-2}e^{-t}dt$ is the exponential integral of the second kind.

Otherwise, alternative methods should be applied.

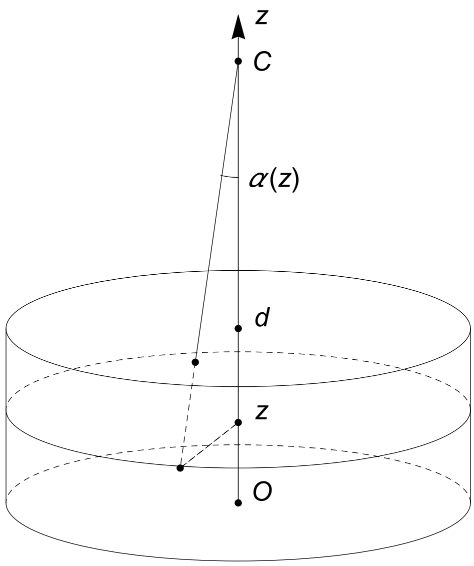


Figure 1. The procedure of evaluation of gamma field for a thick disk. Here d is the disk thickness, O is the origin, $C(0; 0; H + d)$ is the observation point.

In this research, we develop the semi-analytical approach for calculating the integral (3), when q is a function of z. This approach is based on the representation of the function $q(z)$ in the form of the linear combination of step functions. To do this, we use the procedure outlined in [17, 18].

Adopting it to our problem, let us assume that the function $q(z)$ is defined over the range $[0; d]$ and there exist the numbers $\gamma_n = \int_0^d z^n q(z)dz < \infty$. Next, let d_i, $i = 0, 1, \ldots, N$ ($d_0 \equiv 0$, $d_N \equiv d$) be a partition of the domain $[0; d]$. Suppose there exist numbers φ_i such that it is valid the following representation

$$\tilde{q}_N(z) = \varphi_1(\theta(z-d_0)-\theta(z-d_1))+\varphi_2(\theta(z-d_1)-\theta(z-d_2))+\cdots+\varphi_N(\theta(z-d_{N-1})-\theta(z-d_N)), \quad (5)$$

where $\theta(z)$ is the Heaviside function ($\theta(z)$ is 0 for negative z and 1 for positive z).

To get the constraints for the quantities $\varphi_{1,\ldots,N}$ and $d_{1,\ldots,N-1}$ (recall that d_N is fixed), we multiply relation (5) by $(n+1)z^n$, $n = 0, ..., 2N-1$ and each of them integrate over $[0; d]$. The resulting nonlinear algebraic equations can be cast in the form of the following system

$$\begin{gathered}
\varphi_1 d_1 + \varphi_2(d_2 - d_1) + \cdots + \varphi_N(d - d_{N-1}) = \gamma_0, \\
\varphi_1 d_1^2 + \varphi_2(d_2^2 - d_1^2) + \cdots + \varphi_N(d^2 - d_{N-1}^2) = 2\gamma_1, \\
\cdots \\
\varphi_1 d_1^{2N-1} + \varphi_2(d_2^{2N-1} - d_1^{2N-1}) + \cdots + \varphi_N(d^{2N-1} - d_{N-1}^{2N-1}) = (2N-1)\gamma_{2N-2}.
\end{gathered} \quad (6)$$

The solution of this system provides us the partition of interval $[0; d]$ and the weighting factors φ_i for the step functions. Therefore, there is a natural constraint for d_i. They must lay in the interval $[0; d]$, i.e. $0 < d_i < d$. Note also if system (6) possesses the solution $\{d_1, \ldots, d_{N-1}\}$, then any permutation of d_i is the solution as well (φ_i are not preserved).

Considering the subsystems of (6) at small N, it is easy to see that the developed procedure incorporates the approximation (for $N = 1$) of function $q(z)$ by its integral average value γ_0/d on the interval $[0; d]$. The next order of approximation when $N = 2$ leads us to the three equations with respect to $\varphi_{1,2}$ and d_1 which can be evaluated analytically, namely

$$\begin{aligned}
&\varphi_1 = \frac{4\gamma_1^2 - 2\gamma_0\gamma_1 d - 3\gamma_2\gamma_0 + \gamma_0^2 d^2}{2\gamma_1 d^2 - 3\gamma_2 d}, \qquad \varphi_2 = \frac{3\gamma_0\gamma_2 - 4\gamma_1^2}{d(3\gamma_2 - 4\gamma_1 d + \gamma_0 d^2)}, \\
&d_1 = \frac{2\gamma_1 d - 3\gamma_2}{\gamma_0 d - 2\gamma_1}.
\end{aligned} \quad (7)$$

Remark: When $d_1 \to d$, then $\varphi_2 \to \infty$. Indeed, assuming that $d_1 = d$, we arrive at the denominator of φ_2 in (7) is equal to zero.

We have not succeeded in derivating the expressions for the higher orders of approximation yet, since the order of algebraic equations increases quickly. But some simplification still can be made. For instance, for the case $N = 3$, we need to solve five equations with respect to $\varphi_{1,2,3}$ and $d_{1,2}$. Since $\varphi_{1,2,3}$ are included in the system linearly, they are excluded from the system by applying Kramer's rule: $\varphi_k = \Delta_k/\Delta$, $k = 1, 2, 3$, where

$$\Delta = \begin{vmatrix} d_1 & d_2 - d_1 & d - d_2 \\ d_1^2 & d_2^2 - d_1^2 & d^2 - d_2^2 \\ d_1^3 & d_2^3 - d_1^3 & d^3 - d_2^3 \end{vmatrix} = d_1 d_2 d(d_2 - d_1)(d_1 - d)(d_2 - d) \neq 0.$$

Thus, the resulting system consists of two nonlinear equations for $d_{1,2}$. The similar reduction of the number of equations is made for $N > 3$ and the determinant Δ is presented in the appropriate form. Note that it is possible to perform the evaluation of Δ for any N

$$\Delta = \begin{vmatrix} d_1 & d_2-d_1 & \dots & d-d_{N-1} \\ d_1^2 & d_2^2-d_1^2 & \dots & d_N^2-d_{N-1}^2 \\ \dots & \dots & \dots & \dots \\ d_1^N & d_2^N-d_1^N & \dots & d_N^N-d_{N-1}^N \end{vmatrix} = \begin{vmatrix} 1 & 1 & \dots & 1 \\ d_1 & d_2 & \dots & d \\ \dots & \dots & \dots & \dots \\ d_1^{N-1} & d_2^{N-1} & \dots & d^{N-1} \end{vmatrix} \prod_{s=1}^{N} d_s = \prod_{s=1}^{N} d_s \prod_{i>j}(d_i-d_j),$$

where the last determinant is the Vandermonde determinant, $d_N \equiv d$.

Let us apply the developed method to the integral (3), when $q = q_0\, e^{-\beta(d-z)}$ [15] such that the source activity is maximal, q_0, on the disk top and decreases toward the bottom. In this case, the integral (3) can be derived analytically, so that this allows one to compare the results of semi-analytical calculations with exact evaluation. Thus, from (3) it follows [1] that

$$I = \frac{q_0}{2}\int_0^d e^{-\beta(d-z)}\left[E_1\left(\mu H + \nu(d-z)\right) - E_1\left(\frac{\mu H + \nu(d-z)}{\cos\alpha(z)}\right)\right] dz = \\ \frac{q_0}{2\beta}\left[E_1(\mu H) - E_1\left(\frac{\mu H}{\cos\alpha}\right) - e^{-\beta d}\, W_1 + e^{\beta\mu H/\nu}\, W_2\right], \tag{8}$$

where

$$W_1 = E_1(\mu H + \nu d) - E_1\left(\frac{\mu H + \nu d}{\cos\alpha}\right),$$
$$W_2 = E_1\left(\mu H\left\{1+\frac{\beta}{\nu}\right\}\right) - E_1\left((\mu H + \nu d)\left\{1+\frac{\beta}{\nu}\right\}\right) + \\ E_1\left(\mu H\left\{\frac{1}{\cos\alpha}+\frac{\beta}{\nu}\right\}\right) - E_1\left((\mu H + \nu d)\left\{\frac{1}{\cos\alpha}+\frac{\beta}{\nu}\right\}\right).$$

Using the asymptotic expansion $E_1(x) = -\gamma - \ln x - \dots$, ($\gamma = 0.577...$ is the Euler's constant), it is also possible to derive the intencity's value at the disk top, i.e. when $H \to 0$ we have

$$I_0 = \frac{q_0}{2\beta}\Big[\ln\frac{1}{\cos\alpha} - e^{-\beta d}\left(E_1(\nu d) - E_1\left(\frac{\nu d}{\cos\alpha}\right)\right) + \ln\frac{\beta+\nu}{\beta+\nu/\cos\alpha} + \\ E_1\left(\nu d\left\{1+\frac{\beta}{\nu}\right\}\right) - E_1\left(\nu d\left\{\frac{1}{\cos\alpha}+\frac{\beta}{\nu}\right\}\right)\Big]. \tag{9}$$

When $q = \tilde{q}(z)$ defined by (5), integral (3) is transformed into the relation

$$\tilde{I} = \frac{q_0}{2\nu}\sum_{i=1}^{N}\varphi_i\left(E_2(\mu H + \nu(d-z)) - \cos\alpha\, E_2\left(\frac{\mu H + \nu(d-z)}{\cos\alpha}\right)\right)\Big|_{d_{i-1}}^{d_i}, \tag{10}$$

where $d_0 = 0$, $d_N = d$.

Thus, we are going to compare the exact value I derived via (8) and its approximation $\tilde{I}$ evaluated in (10). We do this numerically at the fixed parameters $q_0 = 2$, $\mu = 0.05$, $\nu = 0.005$, and $d = 1$. The studies are conducted for two cases:

(I) $q = q_0 e^{-\beta(d-z)}$, $\beta = 2$, representing the *monotonic* function;

(II) $q = q_0 e^{-\beta(d-z)}(1 + \epsilon(d-z)^4)$, $q_0 = 2$, $\beta = 2$, $\epsilon = 3.5$, which is the *nonmonotonic* function.

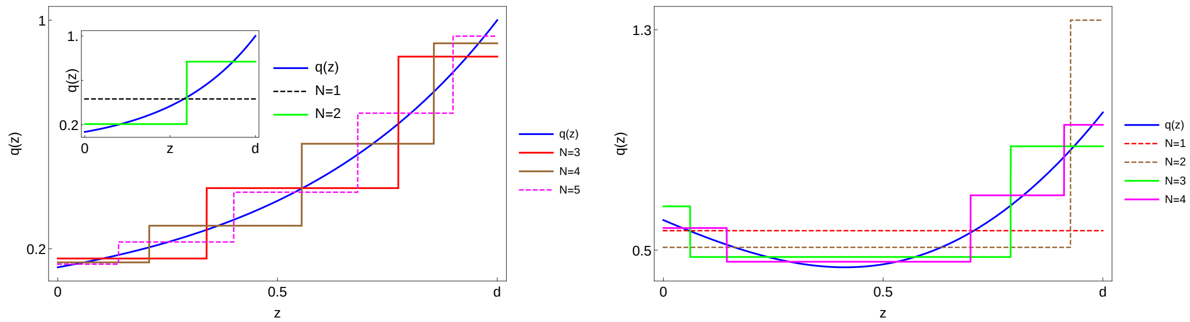
The expressions for the source activity distributions $q(z)$ are chosen in such a way that $q(z)$ is a specified constant at the ground surface $z = d$, i.e., $q(d) = q_0$. These source activity distributions can be related to the depth distributions of radioactive elements such as ^{137}Cs, ^{134}Cs, ^{131}I [19,20], and ^{90}Sr [19] which are typically approximated by exponential-type functions [20, 21].

The angle α is chosen close to $\pi/2$ in order to see the difference between the approximations used. Thus, $\alpha = \pi/2.005$ for the monotonic function q and $\alpha = \pi/2.00005$ for the nonmonotonic one, whereas the parameter H, distance to the disk, is variable in the both cases.

First, we construct the expression (5) for the functions $q(z)$. For case (I), the approximations $\tilde{q}_N$ at $N = 1, 2, 3$ can be derived easily using the elementary integral calculus, formula (7), and the *Mathematica* package command Solve[], respectively. When $N = 4, 5$, the command NSolve[] is used with the initial data for iterations partially taken from the previous step at $(N - 1)$.

The calculations leads us to the following solutions:

$N = 1$: $\varphi = \{0.432\}$;
$N = 2$: $\varphi = \{0.206, 0.768\}$, $\{d_i\} = \{0.597\}$;
$N = 3$: $\varphi = \{0.166, 0.412, 0.872\}$, $\{d_i\} = \{0.339, 0.775\}$;
$N = 4$: $\varphi = \{0.152, 0.281, 0.567, 0.919\}$, $\{d_i\} = \{0.208, 0.555, 0.856\}$;
$N = 5$: $\varphi = \{0.146, 0.224, 0.398, 0.667, 0.944\}$, $\{d_i\} = \{0.138, 0.401, 0.899, 0.683\}$;



(a) (b)

Figure 2. (a): The profiles of monotonic ($q = q_0 e^{-\beta(d-z)}$) (a) and nonmonotonic ($q = q_0 e^{-\beta(d-z)}(1 + \epsilon(d-z)^4)$, $\epsilon = 3.5$) (b) functions and their approximations (5).

The profiles of the function $q(z)$ and its resulting approximations are shown in figure 2a. The quality of approximation can be assessed by analyzing the differences

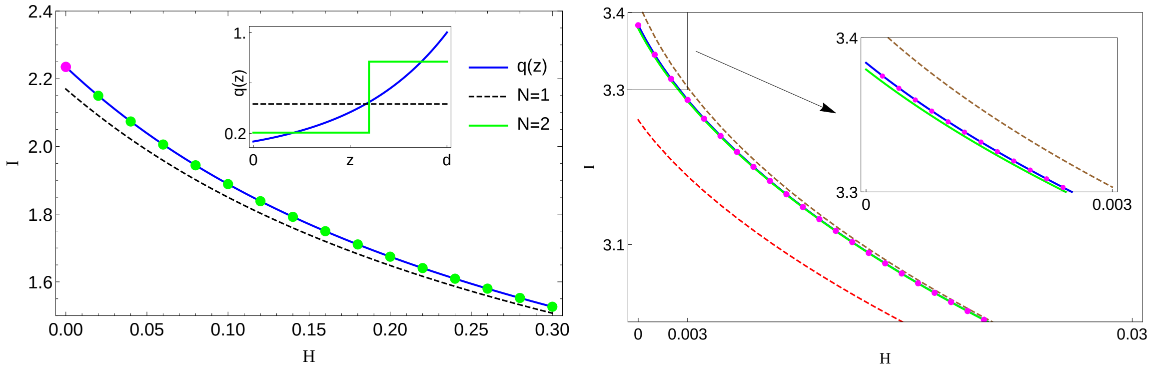
$$\delta_N = \int_0^d (q(z) - \tilde{q}_N(z))^2 dz, \qquad N = 0, \ldots, 4.$$

The corresponding values of δ_N calculated for the exponential function $q(z)$ are given in table 1. It is obvious that as N increases, the δ_N values decrease to zero within the tolerance. This, in turn, means that the approximations $\tilde{q}_N$ approach the function $q(z)$ as N increases.

Table 1. The values of δ_N depending on N.

N	0	1	2	3	4
δ_N	0.0585	0.0194	0.0092	0.0054	0.0036

The same procedure is applied to case (II) and the corresponding approximations are depicted in figure 2b. Here we succeeded in evaluation of $\tilde{q}_N$ only for $N \leq 4$. It can be argued that for a monotonic function the sequence $\tilde{q}_N$, roughly speaking, can be infinite, whereas for a nonmonotonic one only several first elements $\tilde{q}_N$ can be derived properly. For instance, considering the function $q(z)$ from case (II), the number of $\tilde{q}_N$ depends on ϵ, which determines the degree of non-monotonicity. When $N = 2$, we can derive the critical value of ϵ at which $d_1 = d$ in relation (7). From this it follows $\epsilon_{cr} = (2e^2 - 18)/(775 - 105e^2) = 3.786$. Thus, if $\epsilon < \epsilon_{cr}$, then $d_1 < d$ providing the proper solution (7) and in turn $\tilde{q}_N$. If $\epsilon > \epsilon_{cr}$, then $d_1 > d$ and the appropriate approximation does not exist. In other words, we can construct several $\tilde{q}_N$ only for the weakly non-monotonic function q.



(*a*) (*b*)

Figure 3. The dependences of integral (3) when the function $q = q_0 e^{-\beta(d-z)}$ (*a*) and $q = q_0 e^{-\beta(d-z)}(1 + \epsilon(d-z)^4)$, $\epsilon = 3.5$ (see its profile in figure 2b) (*b*).

Next, as soon as the approximation (5) is constructed, the integral (3) is evaluated by the relation (10). Figure 3a shows the dependence (10) on H using the exponential function $q(z)$ (solid curve) and approximations $\tilde{q}_N$ for $N = 1, 2$ (see inset). We see that $\tilde{q}_1$ (dashed curve) is close to the exact curve but the next approximation $\tilde{q}_2$ provides more accurate values depicted with the filled circles. The mostleft point (magenta circle) corresponds to the limiting case when $H \to 0$ and is defined by the relation (9). From the analysis of the figure 3a it follows that the excellent integration results can be achieved starting from the $\tilde{q}_2$ approximation.

The similar calculations are performed for case (II) and are depicted in figure 3b. In this case there are no analytical expressions for the integral (3) calculation, instead, the numerical procedure from the *Mathematica* package (version 7.0 and higher) NIntegrate[] is used. We see that $\tilde{q}_4$ provides the accurate coincidence of numerically evaluated integral (3) and its approximation $\tilde{q}_4$ plotted by filled circles (see inset).

Analyzing figure 3, it is obvious that the most significant difference between exact and approximate integrations is observed near the top of the disk, while this difference decreases as H increases. It is worth noting also that the integration of the parent function $q(z)$ and its approximations for both cases (I) and (II), even at $N = 1$, can provide indistinguishable results when the angle α is not close to $\pi/2$.

4. Concluding remarks

In conclusion, it has been developed the semi-analytical procedure for evaluating the intensity of gamma flux emitted by a cylindrical body with inhomogeneous source activity. In particular, we considered the disk of finite size, the source activity of which depends on the spatial coordinate. According to the procedure developed, the source activity function $q(z)$ is represented as a linear combination of step functions. This allows one to replace the integral, which does not have an analytical representation, by the sum of simpler integrals calculated from their analytical expressions.

We applied the procedure to two cases where the source activity functions were chosen in the form of monotonic and nonmonotonic relations. The former case was represented by the exponential function $q(z)$, while the latter was represented by the product of exponential and polynomial functions. The case with the exponential function $q(z)$ is important since the integral (3) can be derived analytically. This allows one to compare the exact value of the integral and the result of asymptotic evaluation via the procedure.

Experience with the procedure shows that even for a small number of step functions in the representation, the results of calculations are excellent. It is worth to note that the procedure relies essentially on the existence of solutions of nonlinear algebraic system. When the function $q(z)$ is weakly nonmonotonic, the algebraic system is solved successfully. The problem with the system's solving can appear when its dimension is large or the parent function $q(z)$ is essentially nonmonotonic. The description of source activity function with the help of step functions relates to the approximation of disk by the layered medium when the source activity function in each partial layer is constant and coincides with the appropriate weighting factor of step function.

The studies presented above can be interesting for experts in the area of mathematical modeling of gamma fields, as well as for specialists in the organization of environmental monitoring, safety measures, and development of test and calibration installations.

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Collapse behaviour of double-layer pipes: A review

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Abstract. Pipes serve as crucial conduits for fluid transportation across diverse industrial sectors, necessitating a thorough understanding of their structural properties and performance under varying conditions. This study explores the resilience of underwater double-layer pipes, comprising inner and outer layers separated by an annulus that usually used in deep water application such as OTEC and gas and oil transport, against collapse induced by bending moment loads or external pressure. The investigation encompasses a comprehensive review of relevant literature and examines different configurations of DLP. The analysis reveals that key factors influencing the buckling capacity under pure bending loads include pipe length, core thickness ratio, and core stiffness. Under hydrostatic pressure, collapse behavior is influenced by the radius-to-thickness ratio and the ratio of the core thickness to outer and inner layer thicknesses. Furthermore, the collapse mechanism of the double layer pipe is analyzed. The study underscores the importance of addressing such structural nuances in design and operational considerations.

1. Introduction

Pipes serve as essential conduits for fluid transportation across diverse industrial sectors especially in marine industry. They are fabricated from a range of materials, such as Fiber-reinforced plastic (FRP) with high specific strengths and excellent corrosion resistance, ideal for subsea applications across multiple sector [1, 2] or HDPE thermoplastic, known for flexibility and low electrical conductivity [3]. Additionally, pipes are available in various configurations, including single-layer and multi-layer designs. Double-layer pipes find widespread use in sectors like the chemical industry, nuclear power, and renewable energy, such as OTEC due to their ability to withstand extreme temperatures and chemical environments while preventing crack propagation. [4]

A double-layer pipe (DLP) structure refers to a pipe within a pipe, or encased in an outer covering, with an annulus (interstitial space) between the two diameters. There are different types of double layer pipes, each with its own unique features and applications. For instance, a double-layer pre-moulded pipe insulation is used when operating temperatures reach 600°F and above. On the other hand, multi-layer composite pipe systems offer a single solution for all potable water and heating supplies for domestic and light commercial projects, as well as industrial applications such as compressed air and cooling water systems. Multi-layer piping is corrosion-resistant, hygienic, and is not liable to oxygen diffusion through the pipe wall, which minimizes the risk of damage by oxygen corrosion elsewhere in the system. Double containment pipe, also known as double wall pipe or dual containment pipe, is commonly used for handling sensitive materials that may be hazardous or costly if leaks occur.

Double-layer pipes are susceptible to instability or buckling because they exhibit an efficient geometrical shape which allows constructing very thin-walled structures. The buckling phenomenon occurs in any slender structure indifferent to the material. The ultimate strength to resist buckling is the critical constraint and focus of development of such thin-walled cylinders [5]. Buckling can occur due to various loads applied to the pipe structure. For example, internal or external pressure, bending, sheer load, etc. In double layer pipe buckling collapse can happen in structure between inner and outer layer, especially in underwater high-pressure environment that usually where double layer pipe is used. Due to the high usability of double-layer pipe, we need to understand how well double-layer pipe withstands hydrostatic pressure and how it is a behavior of collapsing under high pressure applied outside the pipe. The behavior of sandwich pipes, including buckling, can be analyzed using analytical approaches or finite element formulations [6–9]. This article focuses on studying the collapse behavior of the double layer pipe under bending moment load and external pressure by a comparative study of various articles on pipe failure and various double layer pipe configurations that have been studied.

2. Double-layer pipe configuration and application in brief

The double-layer pipe has various configurations that allow the pipe to have thin walls but strong structural integrity. A DLP is a secondary contained piping system that consists of an inner and an outer pipe with an interstitial space between the inner and outer layer. A double layer pipe is a type of composite pipe with a structural configuration that includes an outer composite pipe, inner composite pipe, and a core. One of the core types used is the iso-grid core that is built from a combination of helical and circumferential stiffeners [6]. In figure 1 the geometric double-layer pipe is shown with iso grid core.

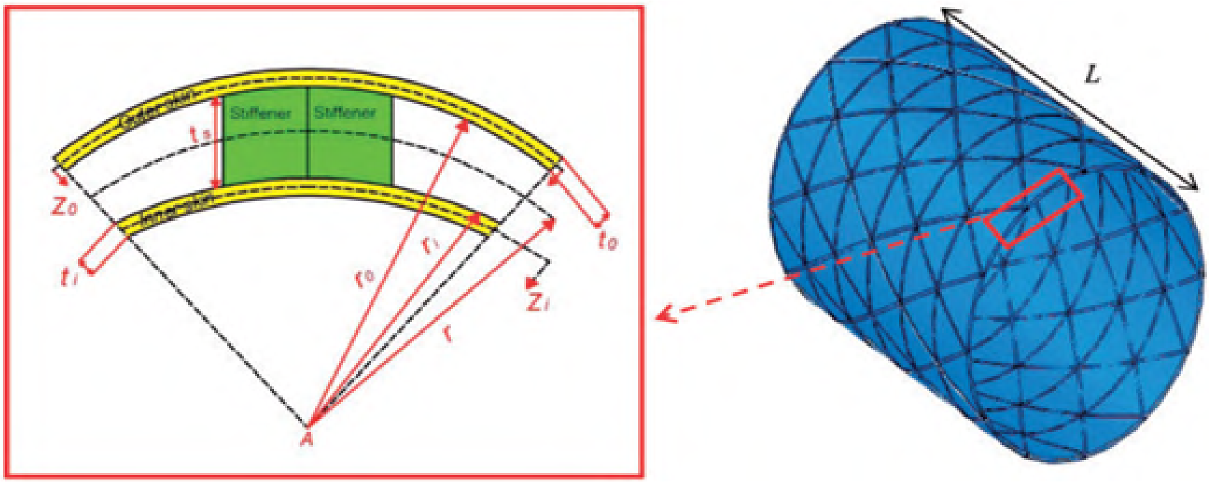


Figure 1. Configuration of the iso-grid sandwich pipe [6].

Figure 1 shows a DLP with a combination of composite outer pipe, composite inner pipe, and isogrid core. The geometric parameter of the pipe are as: L is the pipe length, r is the pipe radius of the middle pipe surface, r_0 is the inner pipe outer radius, r_0 is the outer pipe inner radius, t_0, t_i, and t_s are thickness of the outer pipe, inner pipe, and stiffener. In addition to that, DLP can have many varieties of core material, such as fiber-reinforced cementitious composites, functionally graded interlayers [10], cement annulus [11], compliant core [12], and multiple core pipes [13]. The core material plays a crucial role in the performance of sandwich pipes, and different configurations such as cement annulus or compliance core can be used [11, 12, 14]. In typical DLP structures shown in figure 2. The DLP structure is made up of two layers of plates and a layer of central core. The center core material is thicker and has a lower density than the outer and inner layers, which are thinner panels with greater strength and stiffness. Either glue or welding can be used to join the plates to the core. The moment of inertia of the DLP construction will grow when the thickness is increased for the same mass example. As a result, when compared to a single solid structure made of the same material and weight, the DLP construction has superior bending stiffness and stability.

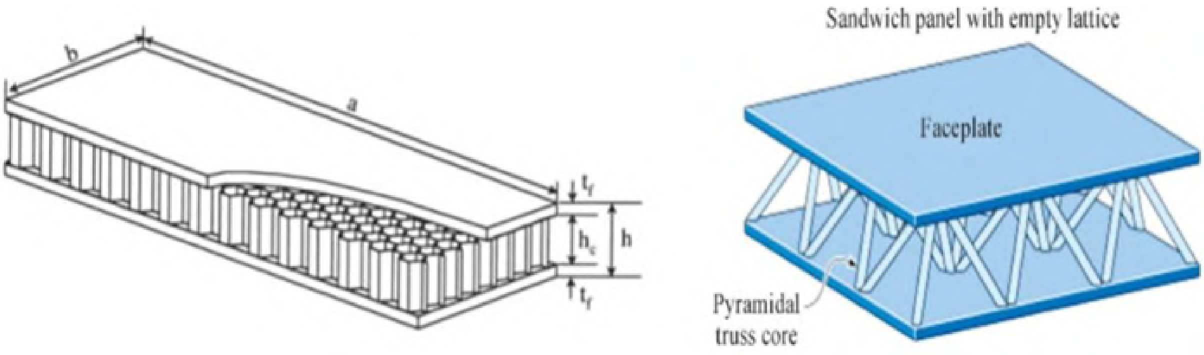
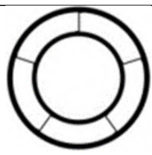
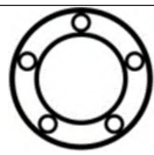
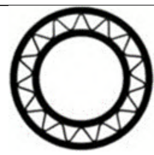


Figure 2. Typical sandwich structure construction [13].

The core structure of a Double Layer Pipe (DLP) can be categorized into various configurations, including I-core, Z-core, O-core, and V-core. Each configuration exhibits distinct core shapes, as depicted in table 1. These configurations are tailored to specific applications, wherein DLPs offer varying characteristics and functionalities. For instance, dual layer external coated pipes find extensive use in the oil and gas industry, providing exceptional resistance against corrosion, cathodic disbondment, as well as abrasion and physical damage. Double wall pipes, also known as dual containment pipes, are prevalent in applications involving sensitive materials, where leakages could pose significant hazards or financial repercussions. Meanwhile, multi-layer composite pipe systems offer versatile solutions for potable water and heating supplies in both residential and commercial settings, alongside industrial applications such as compressed air and cooling water systems. Notably, in ocean thermal energy conversion (OTEC) projects, composite materials are favored for cold-water pipe (CWP) applications due to their high strength and lightweight properties. [15–19].

Table 1. Type of double-layer pipe core configuration [13].

Core type	I	Z	O	V
Illustration				

3. Applied load on double-layer pipe

In an underwater DLP, the predominant load is generated by hydrostatic pressure from the ocean depth crushing and bending moment due to underwater current and its own weight [20]. All that will affect the construction of the DLP itself. Depending on the operational depth of the pipes, it will make a difference in the load received by the pipe, usually the deeper the operational depth of the pipe, the larger it will receive load from its surrounding.

3.1. Bending load

Bending load represents a major load experienced by underwater double-layered pipes (DLP). This load arises the surrounding water's weight, ocean underwater current, and the pipe's own weight. Research on the bending load of DLP is well-documented across numerous publications. Estefen explored the ultimate bending moment for DLP in deepwater contexts [21]. An examined the ultimate bending strength of DLPs reinforced with steel fiber concrete [22]. The buckling and subsequent post-buckling behavior of DLP under a pure bending load were analyzed by Arjomandi and Taheri through the finite element method [23]. Additionally, Cheng and colleagues assessed the ultimate bending strength of DLP, considering the actual behavior between layers [24].

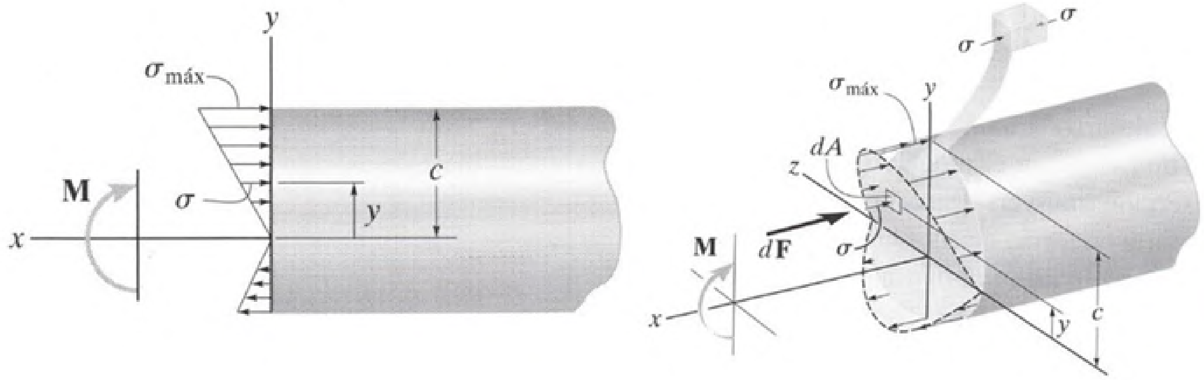


Figure 3. Bending load on DLP [25].

$$\sigma_{Bending} = \frac{M \cdot D}{2I}. \tag{1}$$

According to figure 3, $\sigma_{Bending}$ is the bending stress, M is the bending moment, D is the outer diameter of the pipe, and I is the moment of inertia of the pipe. The distinguishing behavior of pipe under pure bending is the ovalization of the tube's cross-section by the applied called Brazier's effect that reduces the stiffness of the system. This is classified as category I. In this category found that cylinders collapsed when the radially inward deflection reached 2/9 of the cylinder radius [8]. The bending moment that corresponds to the deformation can be calculated by [23]:

$$M_{CR-B} = \frac{2\sqrt{2}}{9} \cdot \frac{E\pi r t^2}{\sqrt{(1-v^2)}}. \tag{2}$$

Referencing equation (2), where M_{CR-B} denotes the critical bending moment, E represents the elastic modulus, r the radius of the pipe, t the thickness of the pipe, and v the Poisson's ratio. In the case of short pipes with a significant $D = t$ value, prone to bending, longitudinal short-wave buckling is observed. With increasing applied moments, the deformation amplitude of the shaft escalates, leading to a catastrophic failure at the critical load. This pipe falls under category II. Consequently, the suggested formula for computing the bending moment is

$$M_{CR} = S\sigma_{CR} = \pi r^2 t \sigma_{CR}, \tag{3}$$

where σ_{CR} is yield stress and can be calculated from

$$\sigma_{CR} = \frac{Et}{r\sqrt{3(1-v^2)}}. \tag{4}$$

3.2. Hydrostatic pressure load

Hydrostatic pressure is pressure exerted by a fluid at rest at a given point within the fluid, due to the force of gravity. It is proportional to the depth measured from the surface, as the weight of the fluid increases when a downward force is applied. That means the deeper a DLP goes the bigger it receives pressure from water outside, The internal pressure of the fluid inside the pipe also plays a role in the hydrostatic pressure that DLP receives so. In OTEC application sandwich pipes used in Cold Water Pipes can reach up to 700 m of ocean depth [26,27]. Castello studied the reeling effect to the strenght of the DLP under external pressure [28] The hydrostatic pressure can be formulated as:

$$P = \rho \cdot g \cdot h. \tag{5}$$

where P is hydrostatic pressure in MPa, ρ is water density at 997 kg/m^3, g is gravity acceleration of 9.87 m/s^2, and h is the water depth in meter.

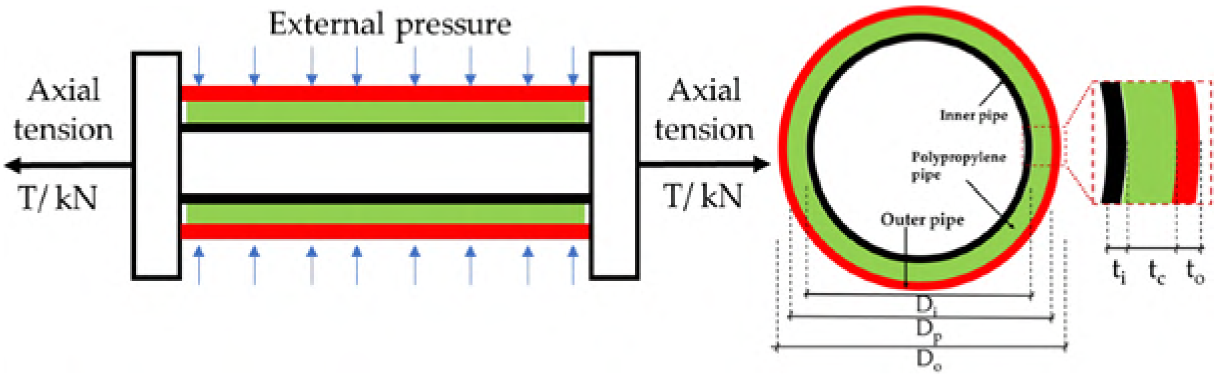


Figure 4. Hydrostatic pressure load on sandwich pipe [29].

As illustrated in figure 4, when hydrostatic pressure is exerted, a pipe may collapse if the disparity between external and internal pressures becomes too large as per the API RP 1111. It is essential that the pipe's collapse pressure surpasses the overall external pressure at all points throughout the pipeline as follows:

$$(P_0 - P_i) \leq f_0 \cdot P_c. \tag{6}$$

Referring to equation (6), P_0 and P_i represent the external and internal pressures respectively. f_0 denotes the collapse factor, and P_C signifies the collapse pressure of the pipe. The equation utilized to approximate the collapse pressure is as follows:

$$P_C = \frac{P_y * P_e}{\sqrt{P_y^2 + P_e^2}}. \tag{7}$$

$$P_y = 2 \cdot S \cdot \frac{t_{min}}{D}. \tag{8}$$

$$P_e = 2 \cdot E \cdot \frac{\frac{t_{min}}{D}}{1 - v^2}. \tag{9}$$

In this equation, P_y represents the collapse pressure at yield, P_e denotes the elastic collapse pressure of the pipe, S signifies the specified minimum yield strength, D stands for the outer diameter, E represents the elastic modulus of the pipe, and v denotes Poisson's ratio.

4. Collapse behaviour

In the previous section, the main load that can be received by DLP consists of bending moment and external pressure. Each of that load will have a different effect of the collapse behaviour of DLP. Usually, it will form a dent in the pipe structure or bending in overall pipe length.

4.1. Collapse behaviour of double-layer pipe under bending load

The buckling behaviour of DLP caused by pure bending load is shown in figure 5. The buckling behaviour and pipe strength are affected by pipe length, core thickness ratio, and core stiffness. The buckling mode shape of the relatively short DLP has short wavelength ripples, meanwhile relatively long DLP does not show any wrinkles along the pipe [23]. As can be seen, the number of wavelengths is changed linearly with respect to the pipe length. This indicates that the buckling moment of longer pipe is smaller than shorter pipe as shown in figure 6a. Core thickness also affects the buckling of DLP. The DLP with thicker core layers show the deformation magnitude of external layer is considerably larger than internal layer, but thinner core thickness show that the deformation profile of internal layer is like external layer in smaller magnitude. Increasing the external layer diameter also increases buckling moment of the system [24]. Core stiffness ratio significantly affects the buckling moment of DLP as well as the buckling mode shape. In this case buckling moment will increase exponentially with the increase of core stiffness ratio as shown in figure 6b.

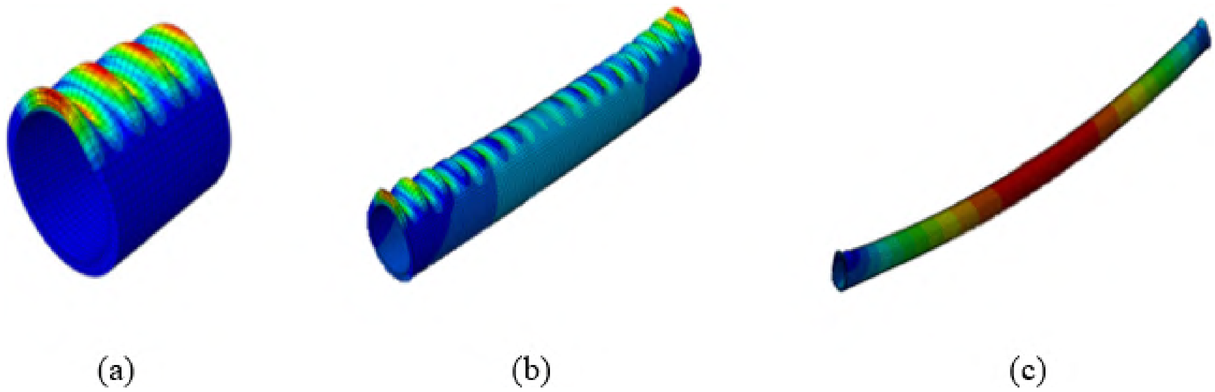


Figure 5. Influence of the pipe length on the collapse behavior of DLP under bending load, (a) L/D=1, (b) L/D=6, and (c) L/D=20 [23].

4.2. Collapse behaviour of double layer pipe under hydrostatics pressure

Numerous research efforts have focused on the stability and post-buckling behavior of DLP when subjected to hydrostatic external pressure. A DLP is sensitive to clearance variations, where minor adjustments in the spacing between layers can significantly affect its maximum strength. Moreover, DLP is prone to imperfections. The outer layer of a DLP possesses greater buckling strength than the inner layer, due to a larger thickness to radius ratio in the outer layer [5]. A linear buckling analysis, depicted in figure 7, illustrates the nodal modes shape of the DLP under external pressure. Generally, the critical buckling pressure diminishes as the radius to thickness ratio increases, as demonstrated in figure 8a. Additionally, the ratio of core to inner

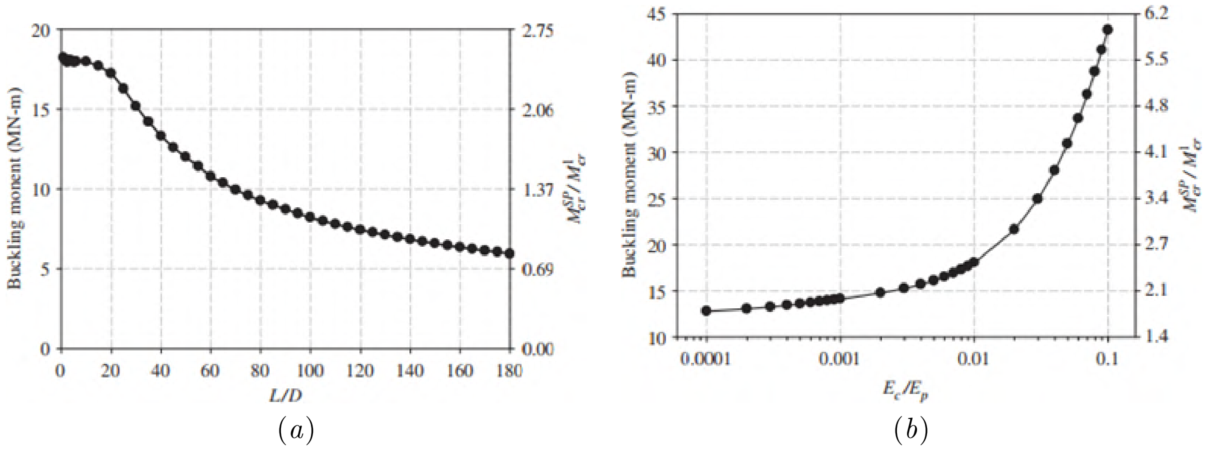


Figure 6. Effect of parameter to buckling moment capacity of sandwich pipe, (a) L/D and (b) core stiffness ratio [23].

and outer thickness influences the buckling pressure of DLP. An increase in this ratio leads to a rise in critical buckling pressure, as indicated infigure 8b [6].

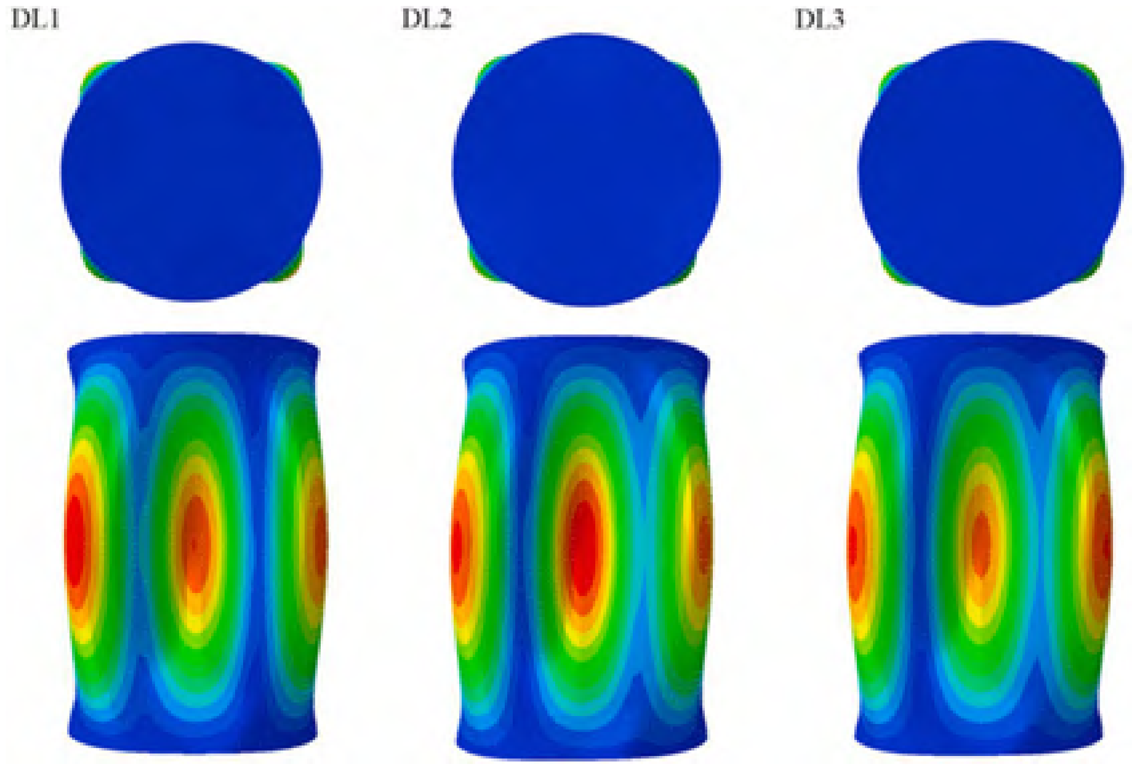


Figure 7. Collapse behavior of DLP under hydrostatic pressure [5].

5. Conclusion

This research explores the buckling characteristics of submerged double-layered pipes when subjected to bending moments and external hydrostatic pressures. The study identifies the primary factors affecting the buckling strength under bending forces are the length of the pipe,

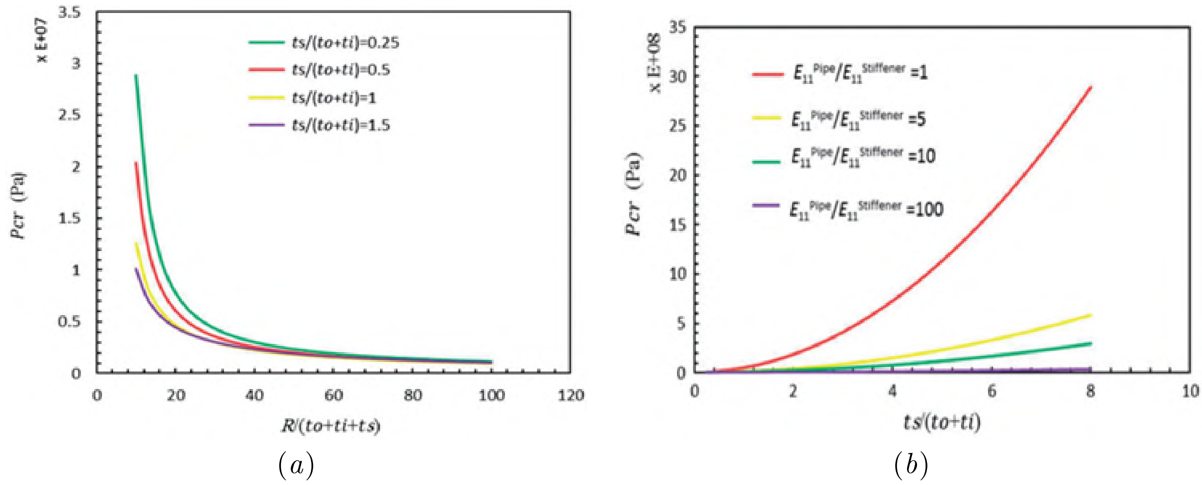


Figure 8. Summarized results, (a) effect of radius to total thickness ratio and (b) core to pipe thickness ratio [6].

the ratio of core thickness, and core stiffness ratio. Pipes with greater lengths have a lower tendency to wrinkle, resulting in a decreased buckling moment. Additionally, an increase in both the core diameter and stiffness enhances the buckling moment. In the presence of hydrostatic pressure, the collapse behavior is determined by the ratio of radius to thickness and the proportion of core thickness relative to the thicknesses of the outer and inner layers. Generally, the critical buckling pressure diminishes as the radius-to-thickness ratio increases, whereas an increase in the ratio of core to outer and inner layer thickness boosts the critical buckling pressures. The research also emphasizes that double-layered pipes are prone to clearances and flaws, underlining the necessity to consider these structural details in both design and operational strategies.

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Research on the effectiveness of using steel reinforcement for strengthening products made of naturale stone

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Research on the effectiveness of using steel reinforcement for strengthening products made of naturale stone

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Abstract. The purpose of this reasearch is to investigate the feasibility of using steel reinforcement to improve the strength characteristics of natural stone products. In the course of the research work, recommendations for preparing samples for strength tests are described. Recommendations for the preparation, configuration, and utilization of the main tools and materials employed during the study are provided. The components of conducting an experiment aimed at determining the strength characteristics of samples have been developed and described. Based on the obtained data, the calculation of the values of the main force parameters during the destruction of samples under the action of bending loads has been performed. According to the results of the research on the methodology of using steel reinforcement to enhance the strength characteristics of stone products, it was established that the ultimate strength and load-bearing capacity of the reinforced samples are significantly higher compared to the similar indicators of unreinforced samples.

1. Introduction

The use of stone products is a crucial element in architectural art because this material not only provides a unique natural appearance but also offers excellent physical and mechanical characteristics, ensuring durability. In recent years, there has been a noticeable trend towards an increased utilization of stone products, particularly in the context of sustainable construction and development.

However, Ukraine, with its territory hosting a significant amount of natural stone suitable for the production of architectural and decorative items (granites, granodiorites, gabbro, labradorites, basalt, sandstone, limestone, etc.), holds substantial potential for the development of stone product manufacturing technologies and their utilization in various spheres. National statistics and research enable a better understanding of the volumes of production and sales of stone products, particularly within the territory of Ukraine, which holds significant reserves of natural decorative and facing stone, estimated at over 500 million cubic meters. Currently, approximately 300 deposits of natural facing stone have already been identified and studied in our country (see, e.g., [1]).

According to the data from the State Statistics Service of Ukraine, the production volume of products made from natural stone exhibited steady growth in the years leading up to the start of the full-scale invasion, with an annual increase within the range of 7-10 percent compared to the previous year. Also, according to the results of research conducted by the Ukrainian Geological

Institute, the most common types of stone products are slabs and blocks, stone products for monuments and window sills, as well as products for decorative interior decoration. As a result, the revenue from the sale of stone products also demonstrated positive dynamics, as confirmed by the data from the Ministry of Economic Development and Trade of Ukraine. According to this data, the gross income solely from the export of stone products from Ukraine in 2021 amounted to 120 million USD (0.59 percent).

The widespread use of products made from natural stone in various aspects of human life is indicative of the leading role of this material in the construction industry and design. This is explained by its moderate cost and excellent operational characteristics. While conducting an analysis of the prospects for the use of natural stone products, it is necessary to consider not only their advantages but also their drawbacks. This includes the low strength of certain types of stone or their susceptibility to specific types of loads, such as bending. This drawback significantly limits the range of possible directions of exploitation of products made of natural stone. One way to enhance the strength characteristics of products made of natural stone is by utilizing reinforcement techniques. The essence of this technique lies in the use of reinforcing dowels capable of providing additional rigidity to stone products. Various materials, such as steel reinforcing dowels, composite materials, fiberglass materials, etc., can be used for reinforcement.

2. Literature review

One of the ways to control the strength characteristics of products made of natural stone is the application of reinforcement techniques. Currently, research on this method is quite relevant, as it is one of the most effective ways to strengthen the structure of natural stone products. As a result, there is a considerable amount of work related to this topic.

One of these is the work of Gaevska, who investigates the possibilities of using carbon fiber for reinforcing products made of natural stone [2]. Gaevska showed that the use of carbon fiber significantly increases the strength of natural stone products. In particular, it was established that the tensile strength of natural stone products reinforced with carbon fiber is 2-3 times higher than the tensile strength of unreinforced products.

The possibility of using reinforced steel for reinforcing products made of natural stone is thoroughly discussed in the article by Varshavska [3]. The article establishes that the use of steel reinforcement significantly increases the strength of natural stone products. In particular, it was shown that the tensile strength of natural stone products reinforced with steel inserts is 1.5-2 times higher than that of unreinforced products. The article also examines the impact of various factors on the strength of products made of natural stone reinforced with steel. In particular, it was determined that the strength of the products is influenced by the number of inserts, their diameter, the method of reinforcement, and the type of natural stone.

From the general literature review, it becomes evident that steel is the most common material for reinforcing products made of natural stone. Steel dowels have high strength and durability, but at the same time, they are quite heavy, which increases the final mass of the product. On the other hand, fiberglass is a lightweight and strong material that is resistant to the influence of aggressive environments, such as seawater or acidic atmospheric precipitation. Basalt fiber can be characterized as a strong and durable material that is not susceptible to corrosion. Basalt fiber is often used for reinforcing products made of natural stone that are subjected to high temperatures. According to preliminary assessments, carbon fiber among the presented options is the strongest material used for reinforcing products made of natural stone.

The choice of material for reinforcing products made of natural stone largely depends on the purpose of the product, its size, external influences to which it will be exposed, as well as the financial capabilities of the customer. The use of reinforcement technology allows for a significant increase in the strength of products and their resistance to deformations. This makes natural stone products more durable and reliable.

The relevance, feasibility, and timeliness of applying the methodology of internal reinforcement to products made of natural stone can be explained by several reasons. Firstly, reinforcement allows for the improvement of product strength, significantly expanding the range of possible applications in construction and architecture. Reinforced products are characterized by significantly higher indicators of strength and resistance to loads compared to unreinforced ones.

Secondly, the reinforcement of stone products can increase their durability and reduce the probability of damage or destruction under the influence of external factors, such as vibration, temperature fluctuations, loads, etc. This increases the durability and ensures the reliability of operation of stone products.

In general, the use of methods of reinforcement of products made of natural stone has a significant potential for improving their characteristics and expanding the scope of their application. Research and further development of this technique is an important task that will contribute to improving the efficiency and reliability of stone products in our time.

3. Methods

The main catalyst for ensuring the sustainable development of any industrial sector, including stone processing, is the need to meet a wide range of societal needs [4–8]. For example, in the field of materials science, there is a consistent and prolonged development facilitated by research aimed at finding ways to create new materials that have improved and often unique characteristics compared to already known and used materials. The logical consequence of this is the emergence of new materials that may be more economically advantageous or have superior operational characteristics such as strength, rigidity, resistance to environmental factors (erosive impact, biological influences, influence of alkaline or acidic environments, etc.), and a longer service life. Given the thousand-year experience of using natural stone in construction, it becomes evident that it is one of the earliest materials employed in creating architectural structures. This is demonstrated by a significant number of architectural monuments that have endured through time. Today, construction continues to be the primary sector driving the consumption of stone mining and stone processing products.

For example, according to data from the Information Resources Management Association (IRMA) (table 1), global production volumes of architectural and decorative products increased by 50 percent from 2000 to 2022. The most significant growth was observed in the period from 2000 to 2010, when production volumes increased by 30 percent. In the subsequent years, the growth occurred more slowly, and in 2022, production volumes reached 5250 thousand m^2 [9].

Ukraine is indeed one of the largest producers of architectural and building products made of stone in Europe. According to the approximate calculations of the State Statistics Service

Table 1. World dynamics of production of architectural and construction products made of stone.

Production volumes, thousand m^2	2000	2005	2010	2015	2020	2022
Facing and modular plates	1100	1500	2350	2580	3300	3500
Step plates	500	700	1140	1250	1570	1650
Window sill plates	250	375	500	625	750	875
Countertops	125	187	250	312	375	437
Balusters	62	93	125	156	187	218
Ritual products	31	46	62	78	93	109
Other architectural and construction products	150	225	300	375	450	525

of Ukraine in 2021, around 140,000 square meters of products made of natural stone were manufactured, accounting for approximately 2 percent of global production. Additionally, according to data from the Institute of Geology of the National Academy of Sciences of Ukraine, the volumes of production of architectural and decorative products made of natural stone increased by 130 percent from 2000 to 2021. The most significant growth occurred in the period from 2000 to 2010, with production volumes increasing by 70 percent. The major processing centers for natural stone are in Zhytomyr, Donetsk, Dnipropetrovsk, Kyiv, and Kharkiv regions.

It is worth noting that in the current stage of development of the construction industry, the increase in the use of architectural and building products made of stone is primarily due to a significant increase in the volume of construction and decorative works. At present, the role of natural stone in the construction industry becomes less significant, explained by its displacement by new, more advanced, and user-friendly materials with better strength characteristics, lower weight, providing greater structural rigidity, and possessing several other equally important advantages [10].

The consistently popular materials include granite, marble, quartzite, and others. These materials continue to have the highest demand among architects and designers, which can be explained by:

- the ability to manufacture and use modular elements, which promotes standardization and reduces assembly time;
- a variety of colors, including traditional white, gray, and brown, as well as vibrant shades like blue, green, and red;
- environmental friendliness, as natural stone is an environmentally clean material without harmful substances and toxic fumes;
- the ability to combine with other materials, such as wood, glass, and metal, to create unique interiors and exteriors.

However, like any material, natural stone has its own characteristics, especially regarding strength and resistance to various loads. The loads to which products made of natural stone are subjected can include weight, wind, thermal, and others, which can affect their mechanical strength and stability.

In view of the above, it can be concluded that natural stone remains a popular material in construction, although its role is not as significant as it was in the past. The use of new materials with improved technical characteristics and greater convenience in application leads to a reduction in the use of natural stone for construction structures.

However, natural stone continues to be an indispensable material for the production of architectural and decorative elements due to its aesthetic qualities, environmental friendliness, and the ability to combine with other materials. The frequency of its application can be increased through the improvement of strength characteristics, including through the method of reinforcement.

The technique of reinforcing products made of natural stone is not something new or revolutionary. For example, external reinforcement of products by covering their backside with special meshes fixed with adhesive mortar has been used for several decades. A similar situation applies to the method of internal reinforcement. European Union countries began paying attention to this method in the early 1990s, but its effective use on an industrial scale is only becoming possible now. One of the main catalysts for the spread of this method is the expansion of the range of materials that can be used as reinforcing inserts, including the emergence of entirely new and promising materials from both technological and economic perspectives.

The proposed method of reinforcing natural stone products will consist of a number of the following technological processes:

- manufacturing the product to the required dimensions and shape;
- performing marking along which cuts will be made for placing reinforcing elements;
- making a cut to half the depth of the workpiece, or to the depth necessary to place the reinforcing dowel in the cut;
- cleaning the cut from residual dust (slurry, etc.) and degreasing it using special solutions;
- preparation of fixing mixture and filling the saw cut with it;
- placement of the reinforcement in the saw cut filled with fixing mixture;
- cleaning the surface of the product from excess fixing mixture;
- storage of samples until the fixing material is completely crystallized;
- processing the surface with a polishing wheel to provide flatness to the back side of the processed sample.

As samples, blanks measuring 600×100×30 mm made from Pokostiv granite were used. The main physical and mechanical characteristics of Pokostiv granite are provided in table 2. Pokostiv granite is quite common in the natural stone market in Ukraine. This granite is known for its excellent characteristics, including strength, durability, and decorative appeal. It is used to manufacture a wide range of products such as monuments, countertops, window sills, facing slabs, and more.

Table 2. Physical and mechanical characteristics of the Pokostivskyi deposit granodiorite.

Parameter	Value min.	Value max.	Unit of measurement
Compressive strength	130	190	MPa
Flexural strength	12	18	MPa
Shear strength	15	22	MPa
Density	2.7	2.8	g/cm^3
Water absorption	0.25	0.35	perc.
Coefficient of friction	0.65	0.7	–

The samples used in the study were manufactured and prepared in accordance with the requirements of the National Standard of Ukraine for products made of natural stone (DSTU B EN 12057:2007) [11]. The surfaces of the samples' faces were sawn. For stone with a maximum grain size of less than 25 mm (the investigated granodiorite of the Pokostivskoye deposit meets this condition), the recommended size of blanks is 50×50×300 mm. However, this did not correspond to the task conditions, so samples of different sizes were made, while adhering to the following requirements:

- the thickness h is in the range of 25 to 100 mm, and it is more than twice the size of the largest grain;
- the total length L is greater than the thickness by at least six times;
- the width b is in the range of 50 mm to three times the thickness ($50\,\text{mm} \leq b \leq 3h$) and is not less than the thickness.

Also, based on the requirements established by DSTU B EN13373, control of deviations of linear dimensions of samples was performed. The values of allowable deviations regarding dimensions, flatness, and perpendicularity deviations can significantly affect the results of strength tests. Accordingly, the deviations of the above dimensions of the samples did not exceed the values given in table 3.

Table 3. Permissible deviations of dimensions and shapes of the tested samples.

Characteristic	Permissible deviation values
Dimension l	$\pm 1\%$
Dimension b	$\pm 1\%$
Dimension d	$\pm 1.5\,\mathrm{mm}$
Flatness	0.15%
Deviation from perpendicularity	0.15%

The selection of the type of reinforcing dowel is a crucial task in terms of reinforcement efficiency. A wide range of various materials can be used for reinforcement, but not all of them allow achieving the desired result. For example, the authors investigated the feasibility of using an aluminum profile to reinforce products made of natural stone. As a result of the study, it was found that such a type of dowel does improve the resistance of natural stone products to bending loads, but the increase in stability is very slight, which is explained by insufficient bonding of the dowel surface with the binding material [12, 13].

Another study specifically explores the strength of the adhesive interaction between different types of surfaces of the reinforcing dowel and the binding mixture. The authors investigated the adhesive ability of composite reinforcement with embedded profile, composite reinforcement with a helical winding at angles of 35° and 80°, composite reinforcement with a sand coating, and steel reinforcement. According to the obtained results, the best adhesion indicators are provided by steel reinforcement (Class A600) and composite reinforcement whose surface is coated with a layer of sand. On the other hand, it is not recommended to use composite reinforcement with a spirally wound winding at angles of 35° and 80°, which forms a helical profile, as it gets cut during pulling out, preventing the full realization of the dowel's rod strength [14].

Therefore, based on the information provided above, it can be concluded that the use of steel reinforcing inserts is reasonable to enhance the strength characteristics of products made of natural stone. Steel reinforcement of class A600 with a diameter of 10 mm was used as the reinforcing dowel (DSTU 3760:2006 "Rolled products for reinforced concrete structures. General technical conditions") [15]. The physical and mechanical characteristics of the reinforcement are presented in table 4, and the cross-section is shown in figure 2.

The further preparation of the samples involved cutting longitudinal grooves along the center of the blank to embed reinforcing elements in them. The grooves were cut using an angle grinder, equipped with a solid carbide disc with a diameter of 125 mm and a continuous working edge. An example of a cross-sectional view of a completed groove and the placement of reinforcing

Table 4. Characteristics of steel reinforcement class A600.

Parameter	Value	Unit of measurement
Yield point	600	$\mathrm{N/mm^2}$
Temporary resistance to fracture	800	$\mathrm{N/mm^2}$
Relative elongation after fracture	12	%
Relative uniform elongation after fracture	4	%
Total relative elongation under maximum load	5	%
Bend angle	45	%
Initial modulus of elasticity	19	$\mathrm{N/mm^2}$

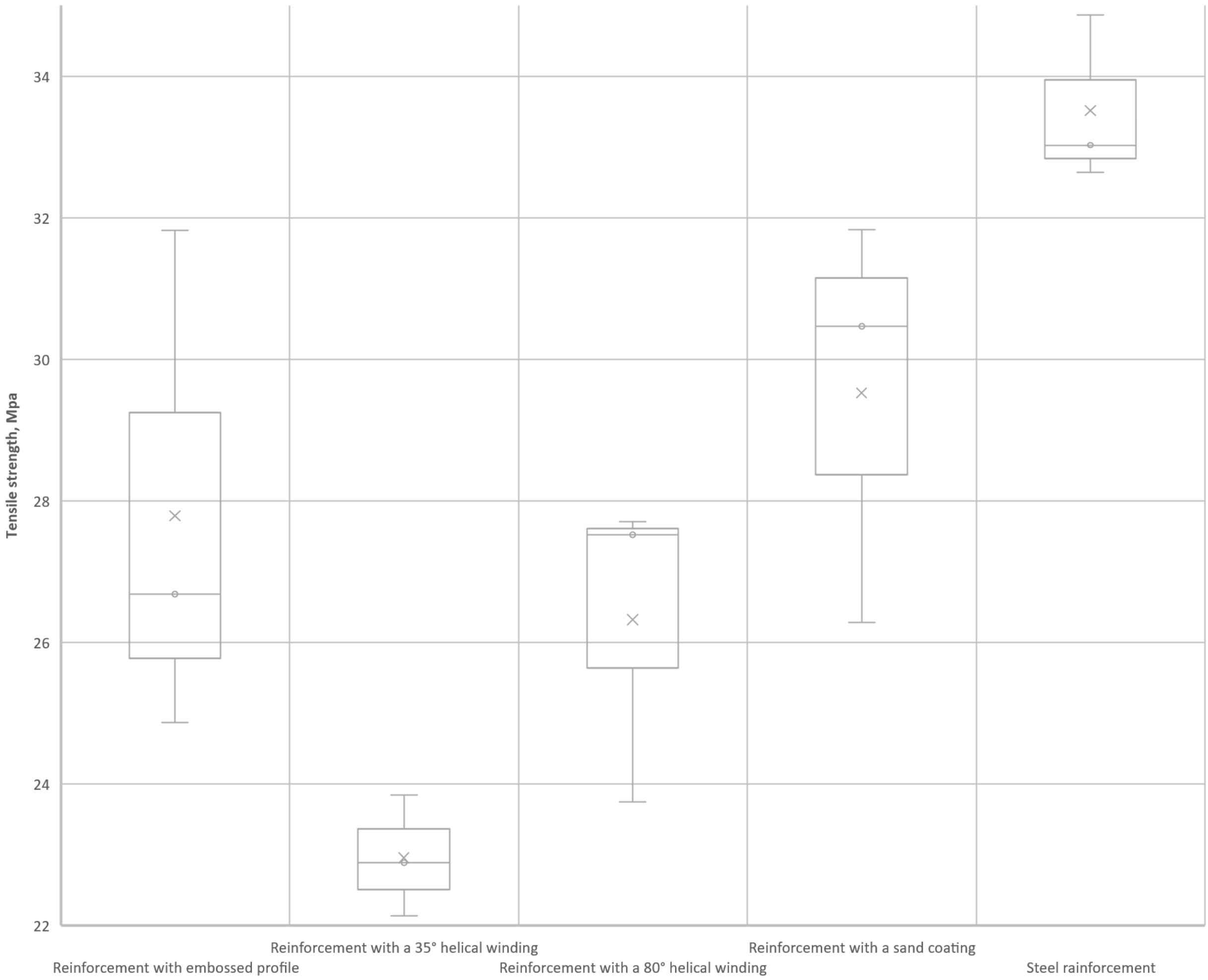


Figure 1. Results of the research of the adhesion interaction magnitude of different types of reinforcing dowels with epoxy binder.

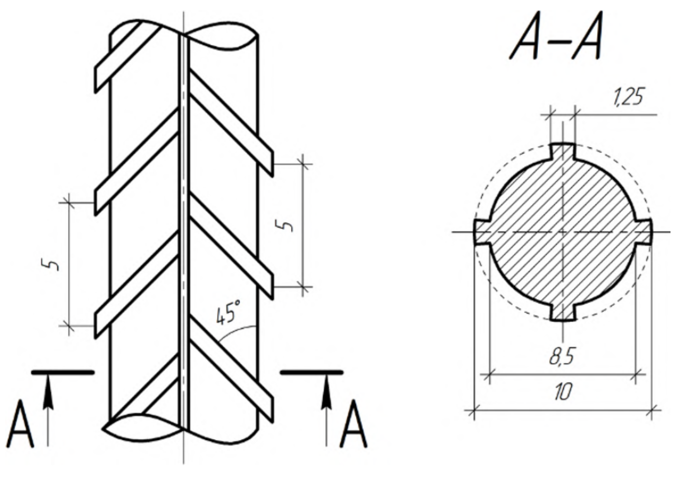
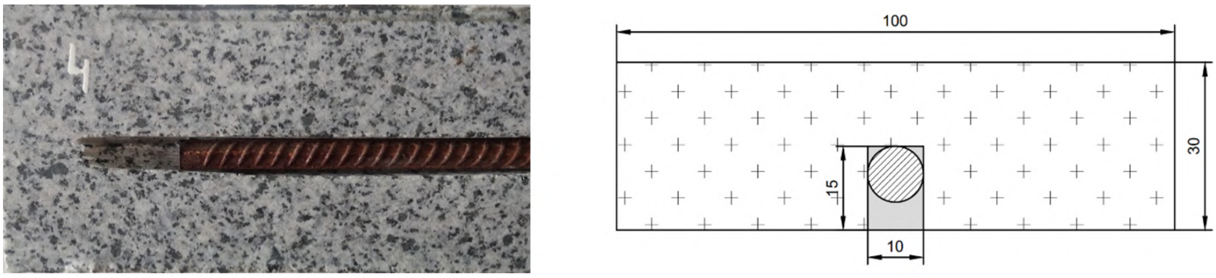


Figure 2. Main linear dimensions of the used steel reinforcement of class A600.



a) b)

Figure 3. Example of reinforcing test samples: a – placement of the dowel in the groove; b – example of a cross-sectional view of a reinforced sample.

elements in it is shown in figure 3.

For fixing the reinforcing dowel inside the groove in this study, white decorative two-component epoxy resin "Fluid Art" was used, the technical characteristics of which are provided in table 5. Before use, this resin was prepared according to the manufacturer's instructions: first, the hardener was added to the resin in a ratio of 1:8, after which the mixture was vigorously stirred for 5 minutes. The application of the mixture in the groove was done in several stages: initially, the empty groove was filled with resin to a depth of 1/3, then the dowel was placed in it, and it was covered with resin to completely fill the groove (a spatula was used to distribute the resin in the groove and clean up excess). After completing the preparatory work, the blanks were kept for 40 minutes (working time of epoxy resin). After that, the blanks were kept for 28 days. Despite the fact that the resin dries and gains initial strength within 1 day, the manufacturer recommends a storage period of at least 28 days for it to acquire its maximum strength.

An important aspect when working with the "Fluid Art" epoxy mixture is to maintain optimal microclimate conditions, specifically the temperature and air humidity, to ensure the accuracy of the technological process and achieve the highest possible quality for the final product. During the preparation of the epoxy mixture, the air temperature was maintained within the range of +18°C to +25°C, and the relative humidity did not exceed 70%. Similar temperature and humidity conditions were upheld during the aging of the blanks.

The determination of the force parameters of reinforced specimens was carried out according to the recommendations of the National Standard of Ukraine "Determination of the strength limit under bending with concentrated load" DSTU B EN 12372:2011 (EN 12372:2006, IDT). The specimens were placed in the center on support rollers (as shown in figure 4). The roller load was applied in the middle of the specimen. The load applied to the blank was increased

Table 5. Physical-mechanical characteristics of the used epoxy resin Fluid Art.

Parameter	Value min.	Value max.	Unit of measurement
Elastic modulus	2.5	3	GPa
Tensile strength	30	50	MPa
Compressive strength	30	50	MPa
Poisson's ratio	0.3	0.35	-
Temperature resistance	50	60	25°C
Linear expansion coefficient	70	80	μm/(m $\cdot$ K)
Viscosity	300	800	MPa $\cdot$ s

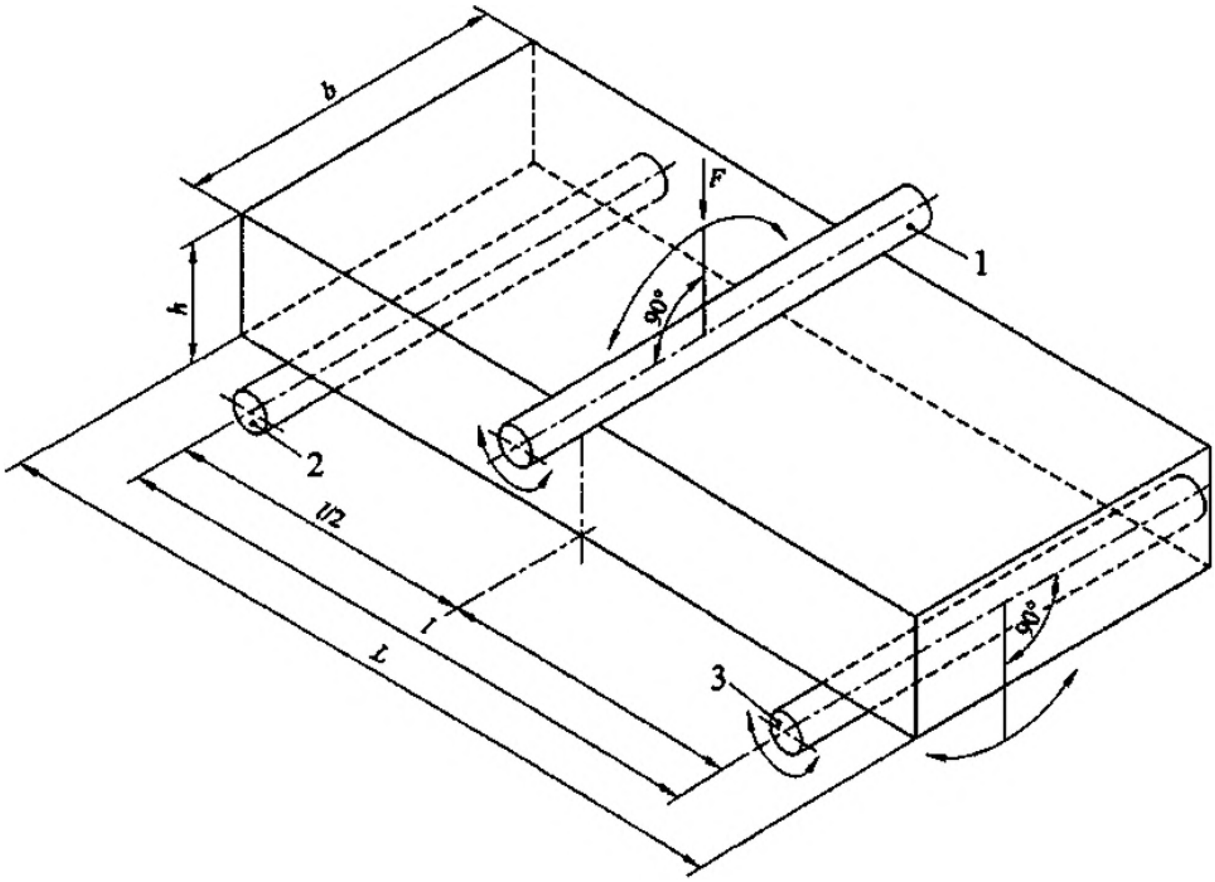


Figure 4. Loading scheme of the test specimen during the determination of the bending strength: 1 – loading roller; 2 and 3 – supporting rollers; b – width of the specimen; h – thickness of the specimen; L – length of the specimen; l – distance between supporting rollers; F – applied force.

uniformly at a rate of (0.25±0.05) MPa/s until the moment of sample failure.

To conduct force experiments, a hydraulic press with a force of 10 tons of the NITRAUM UNY10003 model was utilized. Its initial design did not allow for the necessary research, so a stand was manufactured, consisting of two lower (support) rollers located on a frame made of a rolled beam and one upper (working) roller equidistant from the supports, which actually transmitted the force impact to the specimen (figure 5).

As a measuring device for recording the applied force, a standard pressure gauge installed on the hydraulic press was used and calibrated according to the EN 12390 standard. A Shahe 5306-35 clock-type micrometer with an indicator was employed to measure deformation.

Firstly, unreinforced (control) specimens (figure 6) were studied to establish baseline values and a basis for comparing similar values obtained during the study of reinforced specimens.

From the obtained graph, it can be seen that the unreinforced granite specimen exhibits typical stress-strain behavior, with an initial linear elastic area, followed by a nonlinear plastic area and eventual failure.

The linear elastic area of the stress-strain curve corresponds to the portion where the material behaves elastically, meaning that the deformation is proportional to the applied load. This area is characterized by a constant slope (Young's modulus), which reflects the stiffness of the material.

After reaching a certain point (within the range of 3.8 MPa), the specimen transitions to

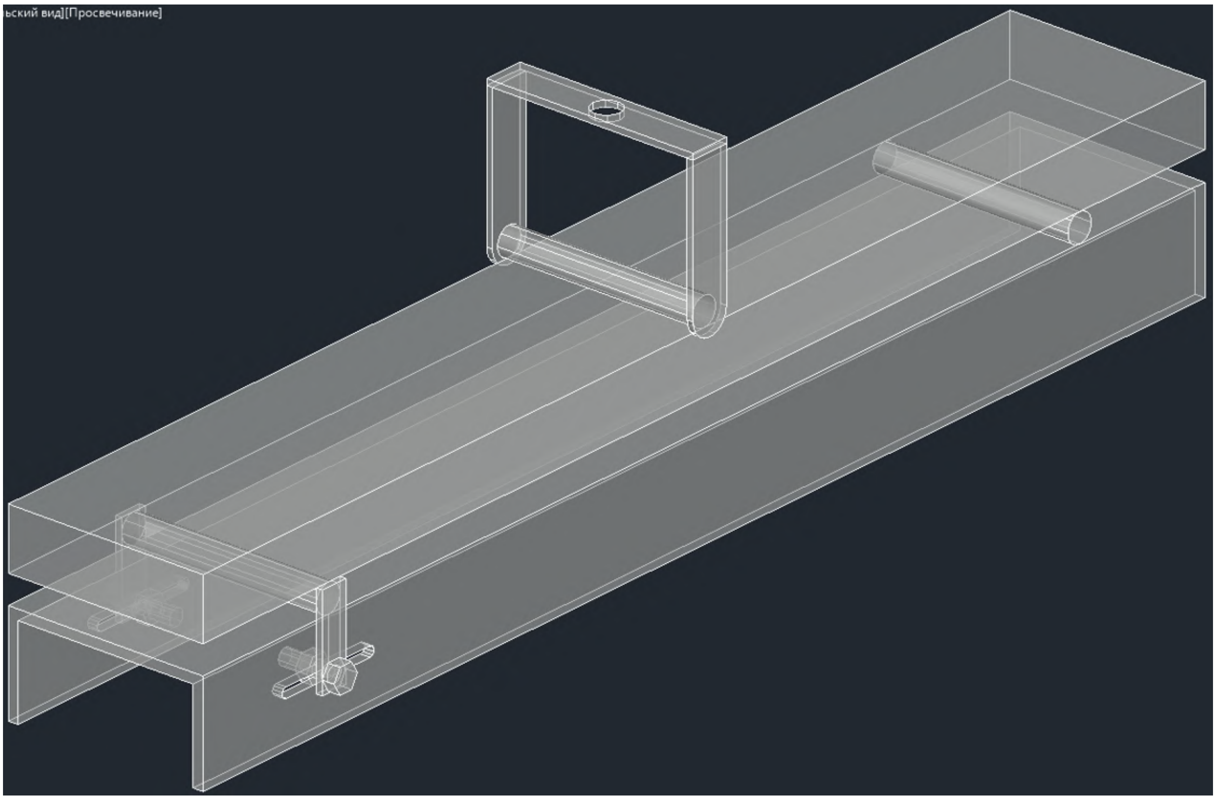


Figure 5. Model of the stand for loading the tested specimens.

a nonlinear plastic deformation area, where the material continues to deform under increased load but at a slower rate. This phenomenon is known as strain hardening, where the material becomes stronger and more resistant to deformation under further loading. In the final stage, unreinforced granite specimens reached their maximum strength and experienced failure in the form of a crack that grew into a fracture (figure 7). The strength of the granite specimen under the given conditions can be determined by analyzing the maximum force achieved during the loading process, which, according to the obtained results, is approximately 4.5 MPa.

The data obtained from the study of specimens reinforced with steel reinforcement was also presented in the form of a graph showing the relationship between the specimen's deformation and the applied load (figure 8).

4. Analysis

The analysis of stress-strain curves for blanks made of natural stone reinforced with steel reinforcement involved identifying typical areas that describe the behavior of the blank. In the initial stage of the stress-strain curves, a linear relationship is observed – the area of elastic behavior of the material. The load within this range increases linearly with the deformation. In this area, specimens retain their original shape after the applied load is removed.

After the elastic area, the stress-strain curve deviates from linearity and demonstrates the yield point. The yield point marks the beginning of plastic deformation, indicating that the material has exceeded the elastic limit. At this point, blanks undergo deformation that will persist even after the load is removed. This specific area of the curve corresponds to plastic deformation, where stone blanks experience significant deformation with a relatively small increase in load.

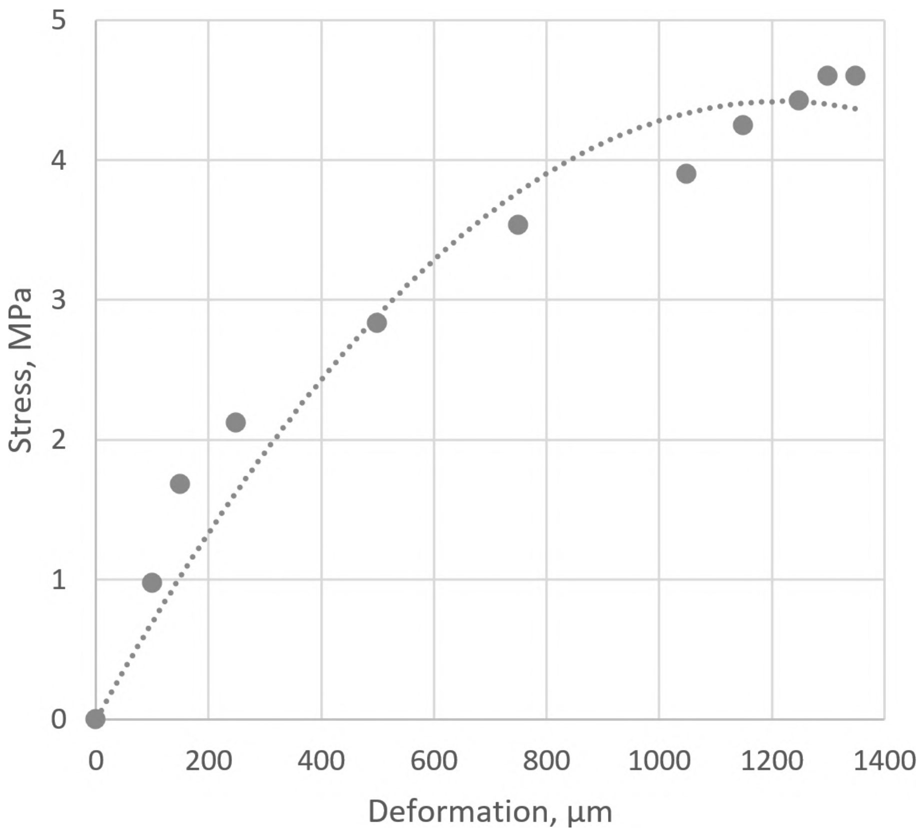


Figure 6. The result of the study of the strength characteristics of unreinforced samples.

Figure 7. Example of failure in unreinforced specimens.

Plastic deformation indicates the material's ability to undergo constant changes in shape without fracturing. The plastic deformation area reaches its peak at the point of maximum stress, which determines the ultimate strength of the specimens.

Beyond the ultimate strength, the curve begins to decline, indicating a decrease in the load-bearing capacity of the blank due to its failure (figure 9).

5. Discussion

The deformation behavior of specimens reinforced with steel reinforcement in all three examined cases follows a common pattern. In the initial stage, the specimens exhibit linear-elastic behavior. With increasing load, they transition into the plastic deformation area, where the

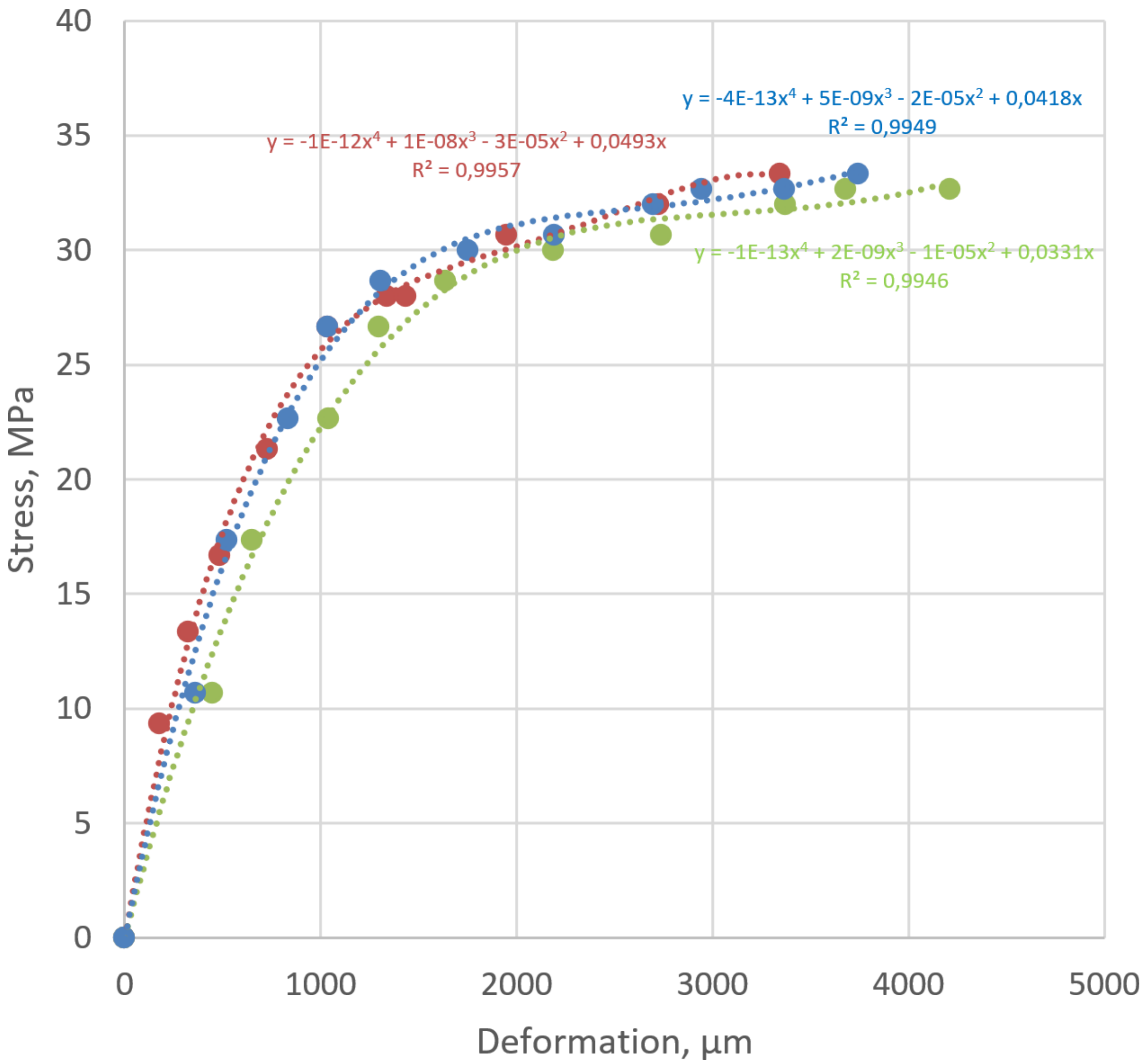


Figure 8. The research results were obtained when testing samples reinforced with steel reinforcement.

stress-strain curve shows a gradual increase in deformation with small increments in load. In the case of the first specimen, the yield strength of 33.3 MPa is reached at a deformation of 3345 µm, after which there is a slight decrease in load, indicating a loss of load-bearing capacity. Similarly, the loading of the third specimen results in a yield strength of 33.3 MPa at a deformation of 3744 µm. The second specimen demonstrates an initial linear-elastic area, but plastic deformation occurs at slightly lower load values, with a maximum of 32.7 MPa. Continuous deformation with slight stress increments is observed until reaching the ultimate strength at a deformation of 4670 µm. The obtained results indicate that specimens reinforced with steel reinforcement exhibit a combination of elastic and plastic characteristics. The steel reinforcement enhances load-bearing capacity and provides plasticity to the specimen.

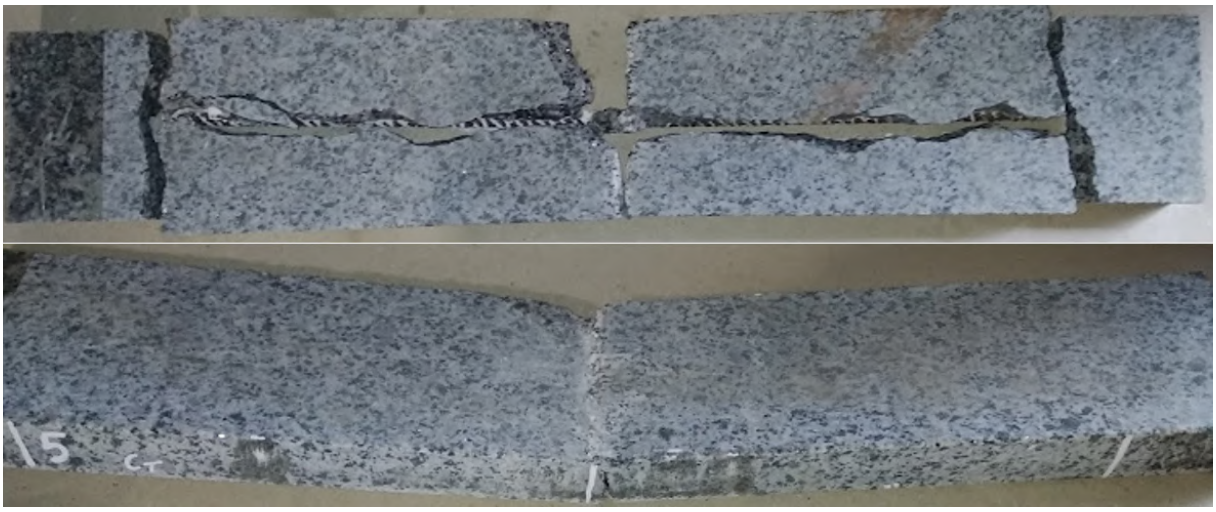


Figure 9. Results of loading specimens reinforced with steel reinforcement feasibility.

6. Conclusions

Comparing the results obtained from the study of specimens made from the granodiorite of the Pokostiv deposit and those reinforced with steel reinforcement, the following conclusions can be drawn:

- the considered type of reinforcing dowel ensures the presence of an initial elastic area;
- the use of steel reinforcement to strengthen stone products ensures a consistent increase in deformation with increasing loads, enhancing the control over the response of plastic deformation;
- the ultimate strength and consequently the load-bearing capacity of specimens reinforced with steel reinforcement are higher than those of unreinforced specimens.

Therefore, reinforcing stone products with steel reinforcement allows for higher ultimate strength, which can be advantageous in cases where maximum load-bearing capacity is required.

In order to improve research results and refine the proposed reinforcement methodology, the following is suggested:

- repeat the experiment using specimens made from other, less robust types of rocks to obtain more diverse data on the strength of different rock types and the feasibility of reinforcing them;
- the textural and structural features of the rock may play a significant role, so investigating the influence of this factor on the effectiveness of reinforcement is also important;
- repeat similar experiments with a larger number of specimens to obtain more statistically significant results and reduce the possibility of random errors;
- in further experiements, examine and measure the impact of various parameters on the strength of specimens, including factors such as loading speed, temperature, etc., as this will provide a more comprehensive understanding of granite characteristics and the possibilities of its reinforcement.

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Reducing the risk of power equipment failure when using information from information measurement system of vibration diagnosis rotating units of auxiliary engines of power plant

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Reducing the risk of power equipment failure when using information from information measurement system of vibration diagnosis rotating units of auxiliary engines of power plant

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Abstract. Sustained operation of critical infrastructure facilities is an extremely important problem. Power Stations are among these facilities. The reliability of Power Station equipment is closely linked to the effective monitoring and diagnostic systems they are equipped. Such systems are constructed in several stages. Good prioritization is an effective way to address security and risk management issues. It aims to maximize the benefits of available resources by focusing on the most important issues and thereby minimizing inherent security risks. Such decisions may be influenced by an inaccurate interpretation of the system state caused by a forced consensus of judgements on an adverse event. In practice, the process of risk management and assessment involves several technical and organizational factors, not just indicators of the severity of an adverse event. The paradigm of risk analysis in the energy sector is clearly related to the risk paradigm that exists in the development of cybersecurity systems. Such decisions may be influenced by an inaccurate interpretation of the system state caused by a forced consensus of judgements on an adverse event. The paper considers the peculiarities of constructing wireless elements of a multilevel diagnostic system for power plant auxiliary motors and the methodology for assessing the auxiliary motor resistance and their impact on the power plant operation.

1. Introduction

The use of diagnostic systems in the construction and operation of engines of various capacities can significantly improve the reliability of such equipment and increase the economic performance of its use. Taking into account the EU-Ukraine Association Agreement signed by Ukraine, the operation of the engines themselves and their diagnostic systems must comply with European standards.

Diagnostic systems of power equipment are developed in several stages: elaborating or application of mathematical models of the systems such as [1–4], selection the most informative diagnostic features based on the analysis of such models, building of training aggregates and decision rules based on the scientific results obtained [5–8]. Probability theory, random process theory, risk theory, statistical hypothesis theory, pattern recognition theory, etc. are used for the problem solution.

The paper discusses the principles of building systems for technical diagnostics of auxiliary motors using autonomous measuring transducers.

Power plant auxiliaries are understood as a complex that includes mechanisms for servicing or automating the operation of the main units and auxiliary devices of the plant, electric motors for these mechanisms, power supplies, intra-station power grid and switchgear, as well as heating, lighting and domestic needs. An important issue is to provide independent power supply to sensor devices. It is provided greater autonomy and increase the service interval of the devices when the system is developed. The use of rechargeable batteries and optimization of power consumption by the devices themselves can only partially solve the problem. Energy Harvesting technologies are currently being actively developed. The use of these technologies can significantly increase the autonomy of sensor units.

2. Features of the structure of the modern power plants and diagnostic system prototype

Any complex technical facility (including a power plant) can almost always be viewed as a hierarchical structure. Power plants contain a large number of units, machines and structural elements. Individual units and components of a power plant together make up certain functional blocks, the reliability of which to a certain extent depends on the reliability of the equipment included in each block, since defects in the component parts are actually defects in the facility as a whole object [9].

The development of a diagnostic system that covers all possible elements of a power plant is too complex a technical problem. Therefore, when a diagnostic system is developed, it is necessary to determine which elements of the object to be diagnosed are critical for its proper functioning and which are less critical.

It is advisable to divide all possible defects in a given object to be diagnosed into three classes: catastrophic defects, non-catastrophic defects, and partial defects from the point of optimizing the complexity of the diagnostic system.

According to the degree of responsibility of the mechanisms, it is advisable to divide this section as follows: particularly responsible mechanisms, responsible mechanisms, non-responsible mechanisms. The proposed methodology for diagnosing the moving units of auxiliary power plant motors is implemented by means of an information and measurement system (IMS). The system has separate units that provide measurement, conversion and transmission of information (hardware) and units that implement software control of the IMS, statistical processing of measured signals and construction of solving rules for determining the technical condition of the equipment being diagnosed (software).

Principles of modularity of the created system were used to ensure the possibility of modifying the IMS to meet the specific needs of the user when prototype of the IMS for vibration diagnostics of electrical equipment is developed (figure 1).

The analogue signal measured at the unit of the electrical machine under diagnosis at the output of the sensor is a DCM (duty cycle modulated) signal. The ADXL202 accelerometer manufactured by Analog Devices was used as the primary sensor. The frequency of the signal is measured by the ADXL202 accelerometer can be set in the range from 0.01 Hz to 6 KHz. It is sufficient to diagnose the technical condition of parts of electric motors: rotor windings' frontal parts, possible thermal imbalance arising from short circuits of individual turns of the rotor winding, as well as rolling bearings.

The sensor unit used in the developed *prototype* of the vibration diagnostics system consists of the following basic elements: two ADXL202 accelerometers; microcontroller PIC16LF873-041 manufactured by Microchip Technology; Bluetooth module EYMF2CAMM-XX manufactured by TAIYO YUDEN; related elements that ensure the functioning of the unit.

The convenience of the sensors with DCM signals from their outputs is due to the fact that

Figure 1. Vibration analysis of the auxiliary electric motor DKRAI – 4519-4V at Darnytska HPP.

such sensors can be directly connected to the input of the microprocessor counter without the use of analogue-to-digital conversion or binding logic chips. It is simplified the process of processing the measured signal and increases the battery life of the devices. Using the created prototype of the IMS, research of the vibration characteristics of auxiliary engines of the Darnytska Heat and Power Plant (HPP) was carried out. The developed vibration module of the prototype of IMS vibration diagnostics was used to measure and analysis of vibration information signals recorded on the bearing units and rotating shaft of the DKRAI-4519-4V electric motor with parameters $P = 710$ kW; $U = 3000$ B; $I = 156$ A; $n = 1490$ rpm. The motor was made in Germany.

According to the international standard ISO 20816-3:2022 [10], which is in force in Ukraine, the DKRAI-4519-4V electric driver belongs to group 1, which corresponds to the power classification. The sensor on the electric driver was also placed in accordance with ISO 20816-3:2022. The vibration signal was analyzed by using a Bartlett window.

The performed measurements and analysis confirm the possibility of using the developed prototype vibration IMS to diagnose rotating units of the auxiliary motor.

3. Method of resilience estimation of the auxiliary electric drivers of power plant

We used the methodology proposed in [11] to assess the impact of auxiliary motors on the power plant's resilience. According to the definition of the US National Academy of Sciences, the structure as a model of the object of study is modelled as a graph $G(N, L)$ where N is the number of nodes connected by links L. The specification N and L includes characteristics related to resilience, such as capacity, location, and the impact of each node and connection lines on the functioning of the object of research. Let C be a set of temporary decision rules and strategies that will be developed to increase the stability of the system during its operation. From a computational point of view, the parameters and algorithms defined by C depend on the specific model being implemented. Ultimately, the system must maintain its critical functionality K at each time step t, where K maps its states or parameters to a real value between 0 and 1. This mapping, for example, can be linear

$$K(t, N, L, C) = \frac{\sum_{i\in(N,L)} w_i(t; C)\pi_i(t; C)}{\sum_{i\in(N,L)} w_i(t; C)} \tag{1}$$

where $\{N, L\}$ is the set of all nodes and links of the graph; $w_i(t, C) \in [0, 1]$ is a measure of the relative importance of a node or link i at time t, $\pi_i(t, C)$ is the degree to which the node is still active in the presence of an attack. An alternative interpretation $\pi_i(t, C)$ is that it is the probability that a node or an link is fully functional. In a more sophisticated formulation, a non-linear and more detailed definition of the critical functionality mapping is also possible.

The paradigm of risk analysis in the energy sector is certainly related to the risk paradigm that exists in the development of cybersecurity systems [11–14]. According to this paradigm, risks, in accordance with ISO/IEC 27000:2022 [15], information security includes three main dimensions: confidentiality, availability and integrity.

- Confidentiality is the property of information to be inaccessible or closed to unauthorised users, entities or processes.
- Availability is the property of being available and ready for use at the request of an authorised entity.
- Integrity is the property of maintaining the correctness and completeness of assets (information).

The additive risk model of information security can be presented as follows:

$$H_c p_c + H_i p_i + H_a p_a = R \tag{2}$$

where $H_c p_c$ is the risk of confidentiality; $H_i p_i$ is integrity risk; $H_a p_a$ is availability risk; R is overall risk; H is amount of losses; p is probability of losses.

The following paradigms are possible to assess the risks of power unit failure:

- $H_c p_c$ is confidentiality risk will correspond to the risk of unauthorised access to the wireless receiver and the technical condition of such a receiver;
- $H_i p_i$ is integrity risk. It is estimated service life and probability of power unit failure;
- $H_a p_a$ is availability risk, it is the actual service life and probability of failure of a power plant, which depends on the operating mode and technical indicators (for example, vibration, according to ISO 20816-3-2022 is included:
  - Operating modes S1-S10 (according to IEC 60034-1-2022 [16]);
  - Temperature indicators (according to IEC 60034-1-2022 [16]);
  - Load characteristics (according to IEC 60034-1-2022 [16]);
  - Vibration characteristics (according to ISO 20816-3-2014 [10]).

It is clear that if there is no information on the availability risk $H_a p_a$ this value can be assigned 100.

If the system does not have any wireless control or diagnostic systems, then $H_c p_c = 0$.

4. Conclusions

The relevance of the results obtained is due to the fact that in the post-war period, one of the main tasks of the country's reconstruction should be the restoration of its United Energy System, including generating equipment. It is necessary to restore generation at a fundamentally new level with the use of advanced achievements of the world and domestic electrical engineering. Such restoration involves restoring not only the main generating equipment, but also auxiliary equipment, which may not be severely damaged during enemy attacks. But it is necessary to assess the risks of its failure and the impact on the functionality of all power equipment. This assessment can be made using the concept of resilience. The expected results can be achieved by increasing the reliability and safety of electrical equipment operation, extending the service life, reducing maintenance costs, through effective planning of repair work and the use of artificial intelligence elements.

It is necessary to use a multi-level structure of the monitoring and diagnostic system, which includes a significant number of autonomous modules for measuring and processing diagnostic information for technical diagnostics of complex energy facilities, such as power plants. These modules must be able to operate for a long time without the need to replace or recharge their batteries. Optimal algorithms and software are of particular importance for the proper functioning of such modules.

The prototype of IMS of vibration signals of diagnostic of auxiliary motors, algorithms for processing vibration signals, elaboration of decision rules, and technical solutions are proposed for monitoring and diagnosing the technical condition of auxiliary engines at the Darnytska HPP.

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Experimental study of the effect of hydraulic gradient on soil hydraulic conductivity

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Abstract. When operating various hydraulic structures, particularly agricultural drains, during the water movement through soils, various types of suffusion deformations typically occur. Particle reorientation and displacement happen under the influence of various forces, including hydraulic gradients. The movement of fine particles, mechanical suffusion, and colmatage were investigated in the hydro-technical laboratory of the National University of Water and Environmental Engineering (Rivne city). Laboratory experiments on filtration using Darcy's facility reveal patterns of the hydraulic gradient's influence on the hydraulic conductivity in soils with different particle size distributions. The article describes the experimental facility and filtration model, outlines the selection of model soil compositions, and the corresponding experimental constructions, along with the conditions for conducting experiments. Based on the research results for selected model soils, the dependence of the hydraulic conductivity on the magnitude of the hydraulic gradient was established. The hydraulic conductivity increases with an increase in the hydraulic gradient, and upon exceeding a certain value of the gradient, known as the critical hydraulic gradient, when soil particles attain a stable position, deformation processes practically cease. It was also found that with a gradual reduction in hydraulic gradients, the hydraulic conductivity remains constant within a certain interval. Only after reaching specific gradient values does the hydraulic conductivity start to decrease, but it exceeds the initial values significantly (up to 32%). This indicates that deformations in the soil caused by mechanical suffusion and colmatage are irreversible.

1. Introduction

When fluid moves through porous media (soils, granular materials of drainage backfills, etc.), various kinds of suffusion deformations usually occur in them: reorientation of particles in space under the action of various forces, and, in particular, hydraulic gradients; movement of small particles, which are referred to as suffusion particles, within the pores of the soil skeleton formed by larger particles – mechanical suffusion; cessation of suffusion particles brought by filtration flow from – colmatage [1, 2]. The consequence of suffusion deformations is a change in the characteristics of the medium, the most general and indicative of which is the hydraulic conductivity (in Ukrainian terminology – filtration coefficient) [3, 4].

Internal erosion is investigated to consider its effect on the performance of drainage [3], and also because of its destructive nature – it is the main cause of failure of many hydraulic structures, in such as dams and levees [1,5,6]. Internal erosion includes four mechanisms, namely, erosion in concentrated leaks, backward erosion, contact erosion, and suffusion [4–6]. Suffusion is a process in which finer soil particles are transported through constrictions between larger soil particles under the influence of filtration forces [7], leading to changes in the physical and geo-mechanical properties of the soils (e.g., permeability, volume change, compressive strength, and soil grain gradation) [1, 8].

The water-regulating capacity of the drain also significantly depends on the permeability of the soil adjacent to the drain [9], which is especially important when working on poorly water-permeable clay soils [10]. With regard to agricultural drainage, wells, and drainage devices in hydraulic structures, suffusion deformations, under certain hydromechanical conditions, are the most influential, especially in the initial period of their operation [3, 11, 12].

In recent years, mathematical modelling of hydraulic processes has been carried out both in general drainage [13] and in particular sufosion phenomena. For such calculations, modelling systems have been created that take into account the influence of a number of factors, including soil gradation on internal erosion, without modelling each particle separately, and the particle parameters are introduced as an additional dimension [14].

When the filtration forces (hydraulic gradients) reach certain critical values, the soil begins to suffusion (i.e., particle transport and changes in the internal structure of the soil). These conditions and critical values make a crucial role in assessing the risks of damage to hydraulic structures and the nature of water inflow to drains and wells. A common criterion for assessing critical suffusion conditions is the gradient, in particular the critical hydraulic gradient (CHG) [1]. CHG is related to internal soil properties and some external factors. During the last decades, the influence of internal properties such as particle size distribution (PSD), gradation, porosity and particle shape has been widely studied using analytical and experimental approaches [1, 7, 8, 15, 16].

Our theoretical studies of filtration in environments where soil deformations occur under the influence of hydraulic gradient and, as a result, changes in its hydraulic conductivity, have established the following. To describe such processes, in addition to the traditional characteristics of the soil (particle size distribution, porosity, hydraulic conductivity, etc.), it is necessary to know additional parameters that determine the property of the soil to change the hydraulic conductivity under the influence of forces from the filtration flow [3]. Such characteristics can be determined using Darcy's facilities if, during soil studies, changes in their hydraulic conductivity are recorded when the hydraulic gradient changes.

2. Materials and methods

To determine the dependencies for filtration flow rates, head functions and their gradients, it is necessary to have reliable systematic research data that reveal the picture of the phenomena that occur around drains in the process of filtration. These data are most expediently obtained using physical filtration models, which, unlike field studies, allow controlling all influencing factors and are built according to the boundary conditions of the filtration problems under consideration. It is practically impossible and impractical to achieve this in the field.

In the series of experiments on filtration models presented in this article, the water flow rate and gradients in the filtration area were determined depending on the change in head at its boundaries. Based on the obtained flow rate q and the head distribution function $h(r)$ (or $h(x, y)$), the following derivatives were calculated: functions of hydraulic gradient distribution $I(r)$, hydraulic conductivity $k(r)$ (respectively $I(x, y), k(x, y)$), additional filtration resistances of the experimental facilities and others.

2.1. Description of the experimental facility

Experiments on the study of filtration flow were performed in the hydrotechnical laboratory of the National University of Water and Environmental Engineering (Rivne) using a special installation (figure 1) [17].

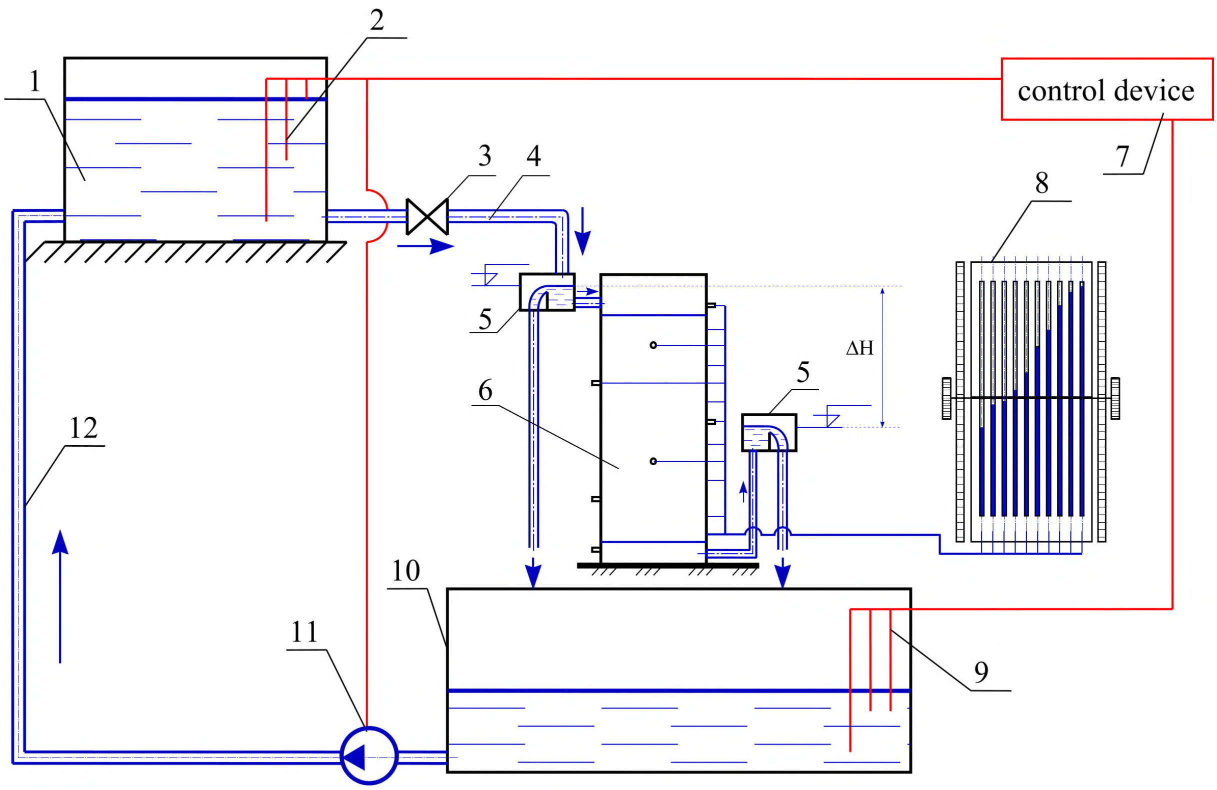

Figure 1. Schematic of the experimental facility: 1 – pressure tank; 2 – level sensor in the pressure tank; 3 – valve; 4 – supply pipeline; 5 – special water overflow; 6 – filtration model (Darcy's facility); 7 – control device; 8 – micromanometer block; 9 – level sensor in the discharge tank; 10 – discharge tank; 11 – pump; 12 – pipeline.

Water from the pressure tank 1 (figure 1) with a volume of $1.0\,m^3$ flows through the pipeline 4 to the filtration model (Darcy‘s facility) 6, from which it is discharged into the drain tank 10 with a volume of $1.0\,m^3$. The flow rate to the model is regulated by the valve 3, and the steady flow rate and pressure are regulated by a special water overflow 5. With the pump 11, water from the drain tank is periodically pumped through the pipeline 12 to the pressure tank 1. Automatic switching on of the pump is provided by the control device 7 and water level sensors 2 and 9.

Such a circular system made it possible to use settled and filtered water in the experiments, the temperature of which was almost constant, which stabilised the effect of air dissolved in water on filtration. The use of water from the centralised water supply system in filtration experiments is unacceptable due to the significant obstruction of the filtration flow of dissolved air, which is concentrated in the small pores of soil from the water [18, 19].

To study the one-dimensional filtration flow, a Darcy's facility was used (figure 2) [17].

The casing of the facility 7 is made of a plastic cylinder with an internal diameter of 23.8 cm and a height of 75 cm. A supporting grid 3 with a layer of filter material (fabric) 2 is attached to the bottom of the cylinder.

Methodological studies of the filtration flow rates at the contact of the experimental soil with the casing and their comparison with the averaged rates in the array have established that contact filtration for the studied soils does not affect the results of the experiments [20].

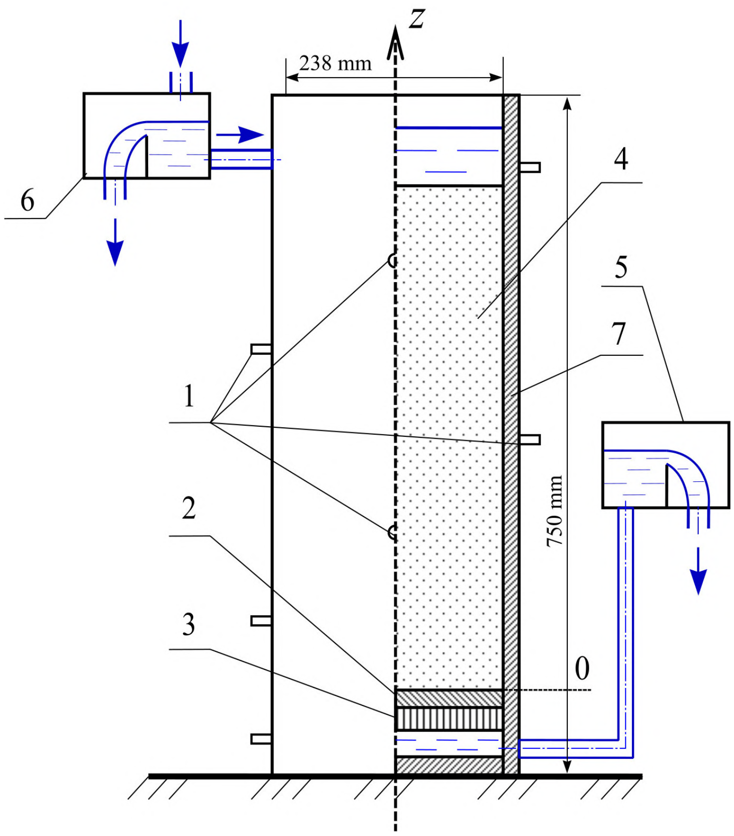

Figure 2. Scheme of the Darcy's facility: 1 – piezometers; 2 – filter fabric; 3 – supporting grid; 4 – test soil; 5; 6 – movable water overflows; 7 – facility casing.

2.2. Model soils and experimental conditions

The soil models used were thoroughly washed homogeneous sands (fractions) with different average diameters and hydraulic conductivity (soils No. 1 to No. 4, No. 6, No. 8 to No. 10), a suffusion soil (No. 7) and natural soil from the experimental site (No. 5), the characteristics of which are given in table 1 and table 2.

Table 1. Particle size distribution of the soil models, percentage.

No. the soil models	Size by sieve analysis, mm										
	less 0.05	0.05-0.063	0.063-0.10	0.10-0.16	0.16-0.20	0.20-0.315	0.315-0.40	0.40-0.63	0.63-1.00	1.0-1.6	1.6-2.0
1	0.0	1.0	1.0	2.0	2.0	17.0	18.0	35.0	22.0	2.0	0.0
2	0.0	0.0	0.0	0.0	1.0	38.0	60.0	1.0	0.0	0.0	0.0
3	0.0	0.0	0.5	13.0	18.5	57.5	6.5	3.0	1.0	0.0	0.0
4	0.0	0.0	1.0	13.0	10.0	27.0	18.0	30.0	1.0	0.0	0.0
5	0.5	1.5	2.5	14.5	8.0	21.0	20.5	18.5	9.0	3.0	1.0
6	0.4	0.4	0.1	6.7	6.0	44.5	25.9	14.0	2.0	0.0	0.0
7	0.0	0.0	5.0	0.0	0.0	0.0	0.1	0.1	21.3	70.7	2.8
8	0.0	0.0	0.0	0.0	6.0	8.3	13.8	27.7	32.3	12.5	4.8
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	63.5	36.5
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	22.5	74.4	3.0

Table 2. Characteristics of soil models.

No. the soil models	hydraulic conductivity		Diameters of particles, mm			Grain size distribution, $\eta = d_{60}/d_{10}$	Porosity, n
	cm/sec	m/day	d_{10}	d_{50}	d_{60}		
1	0.050	43.0	0.224	0.450	0.513	2.29	0.34
2	0.063	54.0	0.0224	0.330	0.344	1.54	0.42
3	0.120	104.0	0.0280	0.550	0.660	2.36	0.41
4	0.025	22.0	0.143	0.230	0.251	1.76	0.39
5	0.023	20.0	0.140	0.310	0.350	2.50	0.40
6	0.003	3.0	0.100	0.240	0.280	2.85	0.36
7	0.016	14.0	0.180	0.300	0.328	1.82	0.40
8	0.600	518.0	0.640	1.050	1.108	1.73	0.45
9	0.134	116.0	0.310	0.625	0.720	2.32	0.41
10	0.850	735.0	–	–	–	–	0.44

The soil hydraulic conductivity given in table 2 are baseline, i.e. those determined in the Darcy's facility at gradients well below the critical gradient.

The formation of the suffusion soil was carried out according to the methodology of G. Pravedny [21]. Initially, a sandy fraction, the characteristics of which are given in table 1 (soil No. 10), was selected to form the skeleton of the suffusion soil.

The calculated diameter of the filtration pores for the particles forming the skeleton was determined by the formula [21]

$$d_0 = 0.455\eta^{1/6}\frac{n}{1-n}d_{17}, \tag{1}$$

where η – is the coefficient of grain size distribution; n – porosity; d_{17} – is the diameter of soil particles less than 17 % by weight.

For example, for model soil No. 10, d_0 is 0.347 mm. The diameters of particles d_{ci} that are capable of moving in the soil and can be taken outside the filtration area at an unprotected outlet are determined by the following relationship

$$d_{ci} \leq 0.77d_0^{max}, \tag{2}$$

where $d_0^{max} = kd_0$ is the diameter of the maximum filtration stroke; $k = 1 + 0,05\eta$ – coefficient of unevenness of particle distribution in the soil or coefficient of localised suffusion (for $\eta \leq 25$).

The calculation according to dependence (2) established that $d_{ci} < 0.29$ mm. Therefore, to obtain a suffusion soil, were added to the skeleton fraction 5 % of particles with diameters in the range of 0.10...0.16 mm. Fine-sandy loamy soils with the content of loamy particles of about 5 % are the most common in the Polissya zone of Ukraine and are the most dangerous in terms of the development of suffusion processes.

Loading of soils into Darcy's facility was performed in layers, with a height of 7...10 cm into water (homogeneous soil) or in a dry state with a gradual increase in the water level (suffusion soil). Each soil layer was flattened, and the removal of air bubbles was carried out.

At the Darcy's facility, the surface of drainage structures with perforation degrees of 0.08% and 0.6% was simulated, corresponding to different plastic drainage pipes. The conditions of the experiments are provided in table 3.

2.3. Measuring equipment

Brass piezometers (figure 3) were utilized for measuring pressures in the Darcy's facility, with their intake section protected by a filter fabric.

Table 3. The conditions of the experiments.

Characteristics of the experiment	Soil No. 3	Soils 1, 2, 4-5, etc.
Height of soil fills, cm	25; 37; 49.5; 60	60
Degree of perforation of structures, %.	0.08; 0.6	0.08; 0.6
Number of layers of the filter fabric	1; 2; 3	1
Number of set pressures	14	14
Number of repeated tests	3-5	3

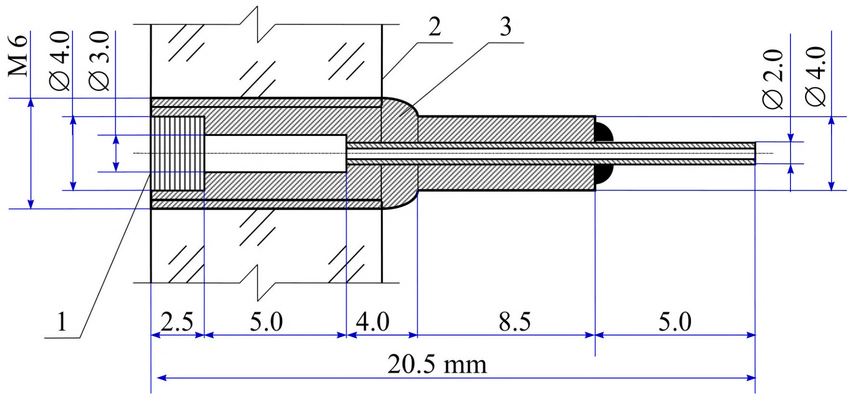

Figure 3. Construction of the piezometer: 1 – the receiving part is protected by a filter fabric; 2 – the wall of the filtration model; 3 – the piezometer body.

At the Darcy's facility, piezometers were mounted on the lateral surface along a screw line, allowing for the averaging of the influence of soil compaction heterogeneity uniformly across the height. The step along the height was 5 cm, with a displacement angle of 30^0 degrees (figure 2, position 1).

Filtration rate was determined using a volumetric method. The water volume was measured with a measuring cylinder of 10 liters capacity for flow rates (Q) greater than 50 cm^3/s, 1-liter graduated cylinders for $Q = 25...50\, cm^3/s$, 0.5 liters for $Q = 5...25\, cm^3/s$, and 0.1 liters for $Q < 5\, cm^3/s$. The filling time of the measuring vessels was measured with a stopwatch with an accuracy of 0.1 s. The water temperature during the experiments was monitored using a mercury thermometer with a division of $0.5\,^0C$.

2.4. Planning and methodology of experiments

Experiments at the Darcy's facility were conducted according to the developed experimental design matrix. The boundary levels and intervals of the investigated factors were established based on prior information obtained from literature sources and hydraulic practice. To compensate for the impact of random errors, simplify mathematical processing, and enhance the accuracy of experimental data, tests were conducted with a uniform triple replication of experiments [22].

The range of variation of ΔH_k was divided into $N = 8$ levels – 0.5; 1.0; 1.5; 2.0; 2.5; 3.0; 3.5; and $4.0cm$. Table 4 provides the experimental plan and the sequence of conducting experiments. The results of the experiments are presented in table 5.

In the table 5 $\overline{V}_j$ – average (arithmetic mean) of the density of the filtration flow; $s_j^2\,(V)\cdot 10^6$ – the average absolute deviation of the experiment; $s_j\,(V)\cdot 10^3$ – standard deviation of the filtration flow.

The methodology for conducting the experiment with non-suffusion sand was as follows.

Table 4. Experiment design matrix with uniform replication.

Number of the experiment	The value ΔH_k, cm							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
1	7	6	3	5	4	8	1	2
2	3	5	2	1	7	4	6	8
3	8	7	4	2	5	3	1	6

Table 5. The results of the investigation of the density of the filtration flow (flux) on the Darcy's facility and their statistical processing.

ΔH_k	Density of the filtration flow (flux) $V \cdot 10^3$, cm/s				$s_j^2(V) \cdot 10^6$,	$s_j(V) \cdot 10^3$
cm	V_1	V_2	V_3	$\bar{V}_j$	$(cm/s)^2$	cm/s
0.5	6.42	6.69	7.92	7.01	0.64	0.80
1.0	13.2	13.9	15.4	14.17	1.26	1.12
1.5	22.7	20.7	19.2	20.87	3.08	1.76
2.0	31.2	29.0	26.0	28.73	6.81	2.61
2.5	39.7	32.1	33.8	35.20	15.91	3,99
3.0	46.8	48.6	46.0	47.13	1.77	1.33
3.5	49.4	50.9	50.2	50.17	0.56	0.75
4.0	55.8	56.5	57.9	56.73	1.14	1.07
					$\sum 31.19$	$\sum 13.43$

Fixed levels (head) were set using movable special water overflow with micrometric screws. After stabilizing the piezometer readings (25-30 minutes), the flow was measured three times with subsequent averaging. To eliminate the influence of uncontrolled boundary effects, the hydraulic conductivity was determined for the middle layer of soil with a thickness of 12 cm. Then, the effective head was increased, and similar measurements were taken under steady conditions. After reaching the maximum head specified by the planning matrix (table 5), the changes were made in the direction of reduction. Water passed through the soil from top to bottom (downward filtration – the direction of filtration force coincides with the direction of the force from the weight of the soil). The temperature of the water was monitored at the beginning and end of each experiment. The methodology for conducting the experiment with suffusion sand is similar. The difference lies in determining the change in the hydraulic conductivity over time for the entire soil fill. After reaching the maximum head specified by the planning matrix and conducting the corresponding measurements, the experiment was completed. The quantity of suffusion particles was controlled layer by layer at the beginning and end of each experiment by determining the particle size distribution of the soil [17].

2.5. Processing of research results

In processing the research results and their generalization, methods of mathematical statistics were used: variance and regression analyses, least squares methods, interpolation, and extrapolation [23–25].

The choice of the experimental area was made based on the density of the filtration flow, which was determined by the formula

$$V = Q/S, \tag{3}$$

where Q – is the filtration rate and S – is the cross-sectional area.

The density of the filtration flow V varied from 0 to 0.064 cm/s for experimental soil No. 3 with a soil fill thickness of 60 cm. Through methodical investigations, the maximum value of head loss H_k on the drainage structure being modeled was determined. The value of H_k was found using the (3):

$$\Delta H_k = \Delta H - \Delta H_0 = \Delta H - V\frac{b_{sf}}{k_0}, \tag{4}$$

where ΔH_k – is the experimental head difference, b_{sf} – is the thickness of the soil fill, k_0 is the soil hydraulic conductivity, determined directly from the experiment at small values of hydraulic gradients.

3. Results and discussion

The void space of granular soils is considered by researchers as a system of deformed tubes, namely capillaries [4, 7, 14, 16, 26]. It is known that laminar flow in capillaries of any Newtonian fluid, including water, follows the Hagen-Poiseuille law, according to which the flow rate is directly proportional to the hydraulic gradient. Therefore, considering non-deformable soil, for the conditions of experiments on the Darcy's facility, we can express it as

$$V = k_0\frac{\Delta H}{L}, \tag{5}$$

where V – is the filtration velocity (which can be regarded as the density of the soil flow [3]); k_0 – is the soil hydraulic conductivity; ΔH – is the pressure difference at the boundary surfaces; L – is the length of the sample of soil.

If the test soil is homogeneous and does not change its properties (cemented sands, solid-porous materials, etc.), the hydraulic conductivity can be determined from (5), the pressure distribution function $h(z)$ is linear, and the density of the soil flow V will increase directly proportional to the increase in pressure difference ΔH.

However, if there is a uniform change in the hydraulic conductivity k throughout the soil under the influence of pressure gradients, the linearity of the function $V(\Delta H)$ is disrupted. In the case of non-uniform changes in k across the filtration area, the linearity of the function $h(z)$ is also disrupted. In this scenario, the Darcy's law can be applied in the form:

$$V = -k\left(I_d\right)\frac{dh}{dz}, \tag{6}$$

where $k\left(I_d\right)$ – is the hydraulic conductivity, which depends on the value of the effective gradient at which deformation processes occur; $h = h(z)$ – is the head function; z – is the coordinate that coincides with the direction of filtration (figure 2).

At the same time, a check was carried out on the water flow regime for all soils. According to various recommendations [3, 27–29], the critical velocity $V_k r$ was determined, and for all test soils, it exceeded the velocity in the experimental facility V_d. In other words, in the experiments, the limit of laminar flow was not exceeded.

Based on the results of laboratory filtration studies in different soils using Darcy's facility, it was established that hydraulic gradients influence the soil hydraulic conductivity, and the linear dependence of $V(\Delta H)$ is disrupted. The hydraulic conductivity is affected both by the overall increase in hydraulic gradients, determined by the pressure difference in the experiments, and their local variation, which can be caused by the resistance of the filtration flow to the supporting grid. Therefore, for further research, we present the values of the hydraulic conductivity k determined for the layer $z = 15...27$ cm, where there is no influence of perforation, in table 6. Figure 4 shows the data processing results of 3 series of experiments on the Darcy's facility with soil No. 10, a fill height of 27 cm, and downward filtration.

The functional relationship $k = k\left(I_d\right)$ will be sought in the form

$$k = k_0\left(1 + b_f I_d\right), \tag{7}$$

Table 6. Results of experiments on the Darcy's facility for soil No. 10.

№	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
V, **cm/s**	0.080	0.153	0.211	0.261	0.305	0.341	0.424	0.495	0.578
I_d	0.099	0.199	0.276	0.342	0.417	0.470	0.579	0.751	0.882
k, **cm/s**	0.806	0.768	0.764	0.763	0.731	0.724	0.732	0.660	0.655
№	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
V, **cm/s**	0.615	0.611	0.073	0.130	0.178	0.220	0.260	0.293	0.358
I_d	0.968	1.00	0.085	0.160	0.226	0.286	0.345	0.391	0.494
k, **cm/s**	0.635	0.605	0.861	0.811	0.787	0.769	0.754	0.748	0.725
№	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
V, **cm/s**	0.435	0.506	0.072	0.133	0.177	0.214	0.247	0.268	0.320
I_d	0.626	0.752	0.085	0.161	0.213	0.264	0.314	0.342	0.412
k, **cm/s**	0.695	0.673	0.844	0.823	0.829	0.811	0.787	0.783	0.778

Using the least squares method, the unknown equation parameters were calculated, which for soil model No. 10 are $k_0 = 0.85\,\text{cm/s}$, $b_i = -0.28$. With the known values of k_0 and b_i, points were calculated using (7) and plotted on the graph (figure 4, position 3). They correspond to the gradients of experimental points 2, with a correlation coefficient $R^2 = 0.964$.

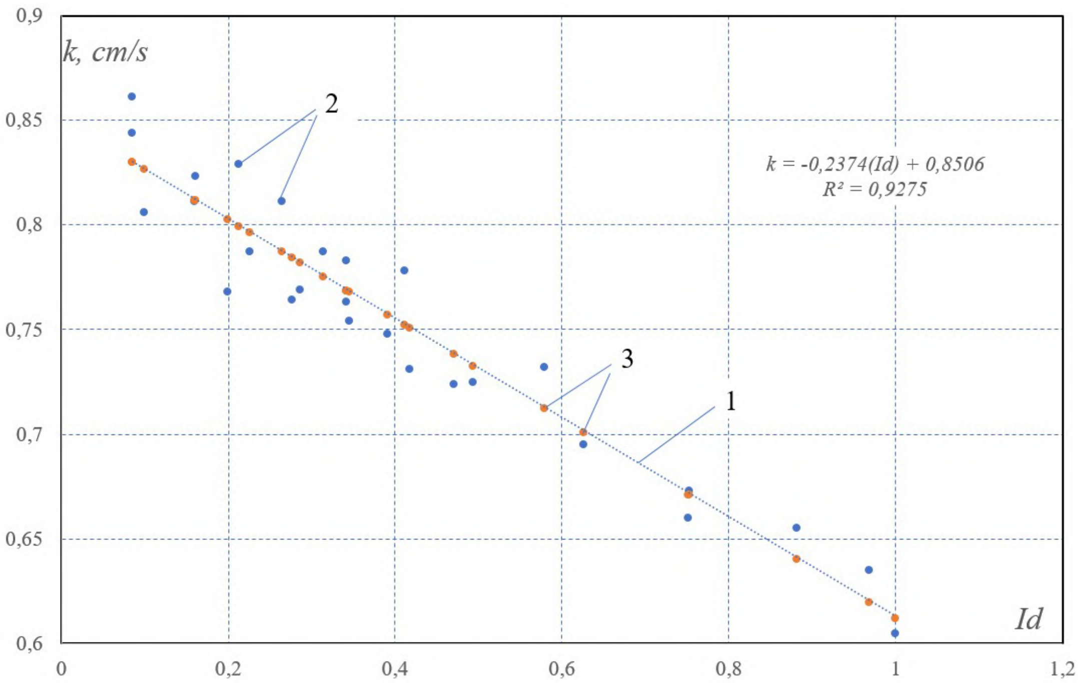

Figure 4. Graphs of the dependence $k = k\,(I_d)$ for soil model No. 10: 1 – theoretical line; 2 – experimental points, 3 – calculated points using (7).

Therefore, for soil No. 10, the average hydraulic conductivity is described by the relationship $k = k_0(1 - 0.28I_d)$, where $k_0 = 0.85$ cm/s. If we substitute the values of $k(I_d)$ into equation (6), we get

$$V = k_0 I_d(1 - 0.28I_d). \tag{8}$$

Figure 5 depicts the graph of the dependence $V(I_d)$ constructed according to (6) – line 1.

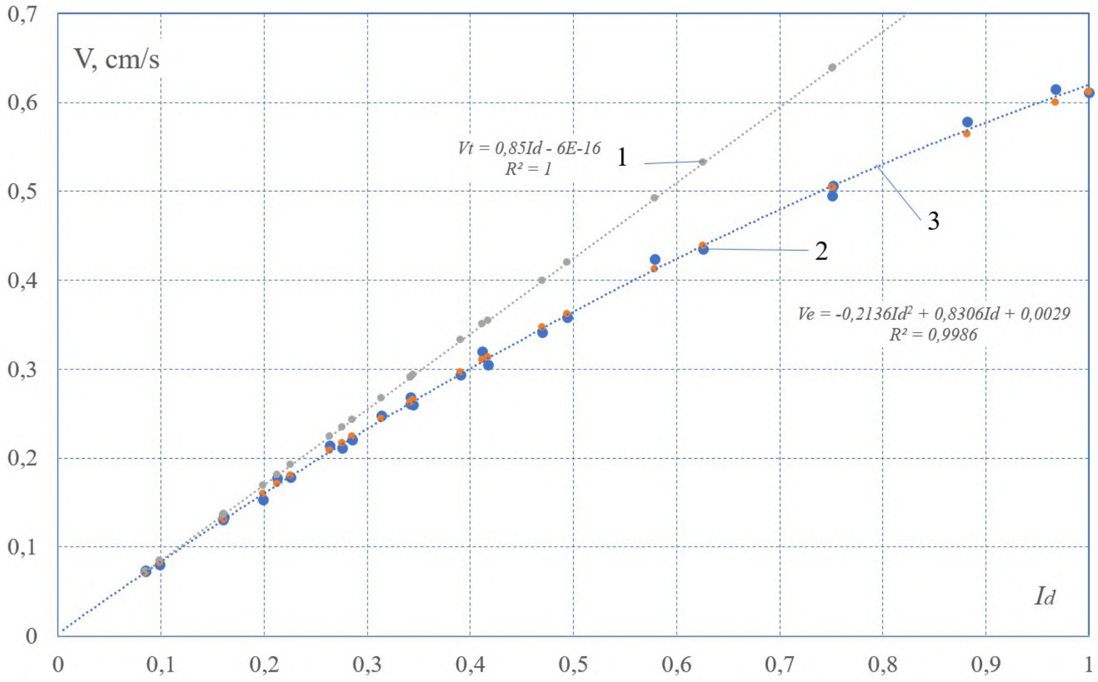

Figure 5. Graphs of $V = V(I_d)$ for soil model No. 10: 1 – theoretical curve, $V = k_0 I_d$; 2 – experimental points; 3 – function $V(I_d)$ according to (8) with $k = k_0 = const$.

Adequacy of the theoretical curve to the experimental points 2 (figure 5) is confirmed by the Fisher criterion. From the graphs (figure 5), it can be seen that when the hydraulic conductivity of soil remains constant $k = k_0$ (assuming no deformations occur), the function $V(I)$ is linear. However, in the presence of deformations, which indeed occur, it becomes nonlinear.

Let's present the results of experiments on the Darcy's facility with soil model No. 6, where the hydraulic conductivity of soil increases with the growth of effective hydraulic gradients. The results of these experiments, conducted according to the conditions in table 3 and where the hydraulic conductivity was determined for the soil layer without the influence of the supporting grid, are shown in figure 6.

Comparing the average values of the hydraulic conductivity $\overline{k_j}$, determined at different effective gradients I_d, allows us to identify the significant changes in the hydraulic conductivity at specific I_d values. The calculation results are presented in table 7, where $\overline{k}$ – represents the average value of $\overline{k_j}$ for the corresponding range of gradient variation.

As we can see from table 7, the soil hydraulic conductivity intensively increases with the elevation of gradients up to a certain value, equal to the experiment for soil model No. 6 $I_d = 2.0$. Further increase in I_d practically does not affect k. This implies that under the influence of the hydraulic gradient, there is a gradual reorientation of particles leading to an increase in the hydraulic conductivity in the direction of the filtration flow. Upon reaching a critical value of gradients (for this case $I_{cr} = 2.0$), particle reorientation has reached its limit, so further increase in I_d does not lead to a change in k. In the range of effective gradients from $I_d = 0$ to $I_d = I_{cr}$, the change in the hydraulic conductivity can be described by (7). Based on the research results, $k_0 = 0.015$ cm/s, $\Delta k_0 = \pm 0.003$ cm/s, $b_f = 0.22$, $\Delta b_f = \pm 0.04$ are determined, and the adequacy of (7) to experimental data with these hydraulic conductivity values is confirmed by the Fisher criterion (calculated value $F_c = 1.72$ is less than the tabulated $F_t = 2.70$ at a 5% significance level).

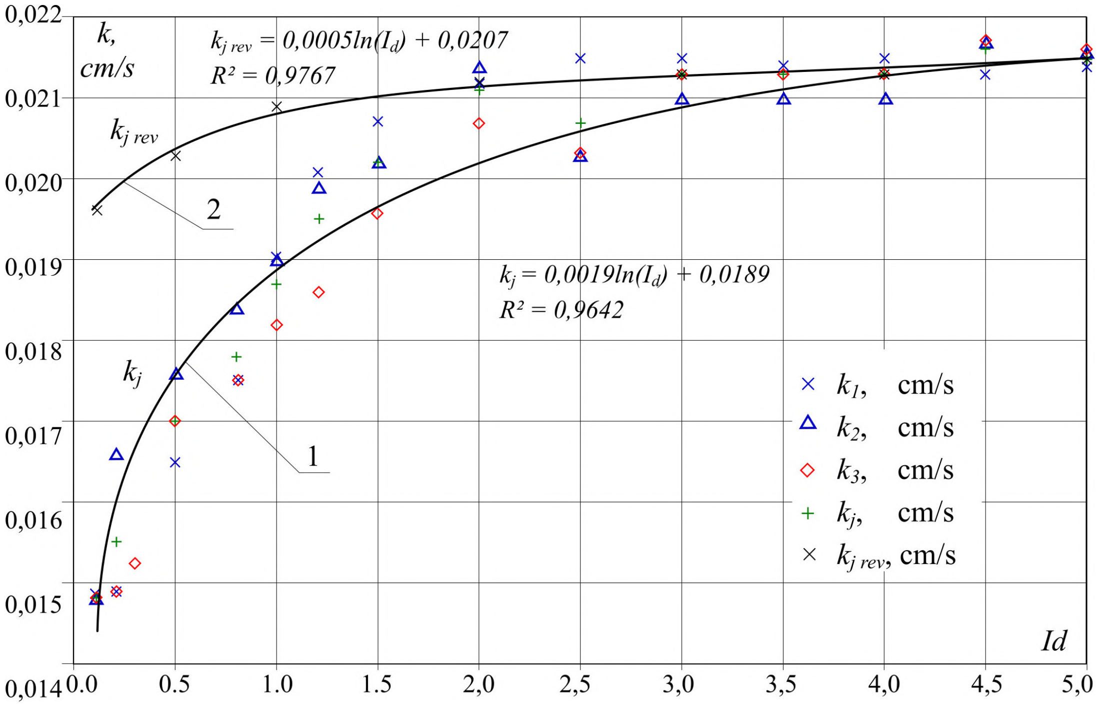

Figure 6. Results of the investigation of the hydraulic conductivity of soil model No. 7 under gradually increasing (pos. 1) and decreasing (pos. 2) gradients.

Table 7. Results of statistical calculations for the average values of the hydraulic conductivity for non-suffosive soil No. 6.

I_d	N	$\overline{k_j}$, cm/s	$\bar{k}$, cm/s	f	s^2, (cm/s)^2	$\overline{s^2}$, (cm/s)^2	F_c	F_t	Conclusions
0.1–2.0	8	0.0148 0.0155 0.0170 0.0178 0.0187 0.0195 0.0202 0.0211	0.0181	16	3.55×10^{-7}	1.49×10^{-5}	41.9	2.7	The changes are significant
2.0–5.0	7	0.0211 0.0207 0.0213 0.0213 0.0213 0.0215 0.0216	0.0213	14	1.24×10^{-7}	2.59×10^{-7}	2.1	2.9	The changes are not significant

For this particular case, when there is actually an upper critical gradient at which deformations cease (unlike the traditional critical value where deformations displacement of colloidal particles begin), it is expedient to express (7) in the form:

$$k(I_d) = k_2(1 + b_f(I_d - I_{cr})), \quad 0 < I_d < I_{cr}, \tag{9}$$

where k_2 – is the stabilized value of the soil hydraulic conductivity for $I_d > I_{cr}$; b_f =

$(k_2 - k_0)/I_{cr}$ – is the coefficient characterizing the intensity of the soil hydraulic conductivity change in the soil with a change in the effective hydraulic gradient.

After reaching the maximum gradient, according to the experimental design matrix, there was a gradual stepwise decrease. The average values of the soil hydraulic conductivity for this case are presented in figure 6, item $k_{j\,rev}$, curve 2.

4. Conclusions

- During the research, it was established that deformation processes occur in the soil around drains, significantly affecting filtration rates.
- It was found that the variation in the soil hydraulic conductivity is influenced by the magnitude of the hydraulic gradient. The hydraulic conductivity increases with an increase in the hydraulic gradient (soil model No. 6), and upon exceeding a certain value of the gradient (for soil model No. 6, $I_{\mathrm{cr}} = 2.0$), soil particles attain a stable position, and deformation processes practically cease (figure 6).
- When reducing hydraulic gradients from maximum values to $I_{\mathrm{cr\ rev}} < I_{\mathrm{cr}}$ (for soil model No. 6, $I_{\mathrm{cr\ rev}} = 1.5$), the soil hydraulic conductivity remains constant. With further reduction, it starts to decrease but does not return to its initial value, exceeding k_0 by 32% at $I_d \to 0$. This indicates that deformations in the soil are irreversible.
- In the course of the research, it was revealed that the major soil deformations occur in the lower zone of the Darcy's facility, i.e., above the filtration device (item 2, 3, figure 2). This zone, due to soil deformations caused by the suffusion processes, has become significantly different from the soil above it. Therefore, in further investigations, we will more closely examine this zone and, overall, the distribution of changes resulting from suffusion and colmatage in soils along the height.

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Investigation of changes in the intensity of polished surface glow of natural stone depending on the intensity of its heating

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Investigation of changes in the intensity of polished surface glow of natural stone depending on the intensity of its heating

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Abstract. In this publication, the authors consider the influence of high temperatures on the change in the intensity of the gloss of the front surface of products made of acidic and basic rocks of natural stone. Changes in gloss intensity were analyzed for each of the control points of heating for the front surface of samples of acidic and basic rocks of natural stone. The main factors affecting the change in the intensity of the gloss of the front surface of products made of acidic and basic natural stone are determined. It has been established that when heated (exposure to high temperatures), acidic rocks of natural stone lose their luster less intensively than rocks with a basic composition. The greatest loss of luster upon heating (exposure to high temperatures) is characteristic of labradorite. On the basis of the obtained values, it is possible to predict the change in the intensity of the gloss of the front polished surface of products from basic and acidic natural stone after exposure to high temperatures, as well as to control the quality of the front surface of natural stone products to obtain products with specified parameters for restoration or restoration work.

1. Introduction

Natural facing and decorative stone today is recognized as a high-quality and durable natural building material widely used for decorative purposes in the embellishment of many buildings and structures. Therefore, in addition to its physical and mechanical indicators, its aesthetic and decorative characteristics play a crucial role in selecting its application locations.

The decorative features of natural stone are determined by such factors as color, pattern texture, structure, translucency, and the degree of surface polishing, precisely defined by the gloss intensity indicator [1, 2].

Various aggressive environmental factors affect the facing surface of products made from natural stone, leading to changes in their decorative and aesthetic properties. One such factor is high temperatures, resulting from fires caused by both human activities and aggression from the Russian Federation. Hence, it is essential to predict how the decorative properties of the facing surface of products made from natural stone will change and accordingly develop recommendations for the use of different varieties of natural stone, as well as restoration guidelines.

Furthermore, the research has practical implications. Firstly, based on the obtained values, it is possible to predict changes in the intensity of gloss on the facing polished surface of products made from basic and acidic varieties of natural stone after exposure to high temperatures.

Secondly, scientifically grounded recommendations can be developed for quality control of the facing surface of products made from natural stone to achieve products with specified parameters for restoration or repair work.

2. Related work

A considerable number of publications have been dedicated to studying the impact of high temperatures on the facing surface of natural stone. For instance, in the study [3], a methodology is described that allows for the control of iron oxidation intensity in products made from labradorite using temperature values. The findings of this research enable the development of a comprehensive set of recommendations for modifying the aesthetic and decorative characteristics of labradorite products. However, these studies primarily focus on color changes and the analysis of the appearance of defects such as red and brown spots [4–13], with little consideration given to the alteration of gloss intensity during these processes.

Most of the preceding research involved heating samples to specified temperature levels, followed by testing them at room temperature. Studies on testing granites [4, 5], limestones, marbles, and gabbros [6, 7] indicate that at temperatures up to 300 °C, stone samples undergo minimal damage. However, in the temperature range of 400–600 °C, microstructural changes and irreversible thermally induced microcracks occur due to differential thermal expansion of minerals. In labradorites, microcracks between minerals are visually observed at a temperature of 600 °C. Nevertheless, less attention has been given to determining the intensity of gloss change on the facing surface of natural stone under the influence of high temperatures.

3. Results

The objective of this research was to establish the fundamental dependencies characterizing the change in gloss intensity of the polished surface of acidic and basic variants of natural stone samples based on the intensity of their heating. Measurement of the reflective (gloss intensity) capability of the polished surface is based on comparing the obtained values with a gloss meter against the benchmark of an etalon surface. Gloss intensity depends on the mineral composition of different variants of natural stone, the processing methods, and changes under the influence of aggressive external factors. To establish the fundamental dependencies characterizing the change in gloss intensity of the polished surface of acidic and basic variants of natural stone samples based on the intensity of their heating, 20 samples were selected from four natural stone deposits (5 samples from each deposit).

The chosen samples include acidic variants from the Leznikivsky and Maslavsky granite deposits and basic variants from the Katerinivsky labradorite and Irshynsky gabbro deposits. The sample dimensions were 15x15 cm.

The polishing process was carried out on a column-lever machine using diamond tools. Gloss was measured with a photometric gloss meter BF5-45/0/45. Heating was performed in an electric furnace at a rate of 1°C/min. The samples were held at temperatures of 200, 400, 600, and 800 °C for one hour, followed by cooling to 20 °C at a rate of 1 °C/min. Before measuring gloss, the device was calibrated on a black-colored sample included with the instrument, having a gloss value of 97 units. Gloss was measured at five points on each natural stone sample, and measurements were conducted for five samples from each deposit. The obtained results were averaged.

Upon analyzing the data on the initial gloss measurements (zero point) in control samples, it was found that the highest gloss value is present on the polished surface of samples from the Irshynsky gabbro deposit, while the lowest gloss value is observed on samples from the Leznikivsky granite deposit (figure 1).

After measuring and statistically processing the measurement data, graphical dependencies were obtained, characterizing the change in the intensity of gloss on the polished surface of acidic

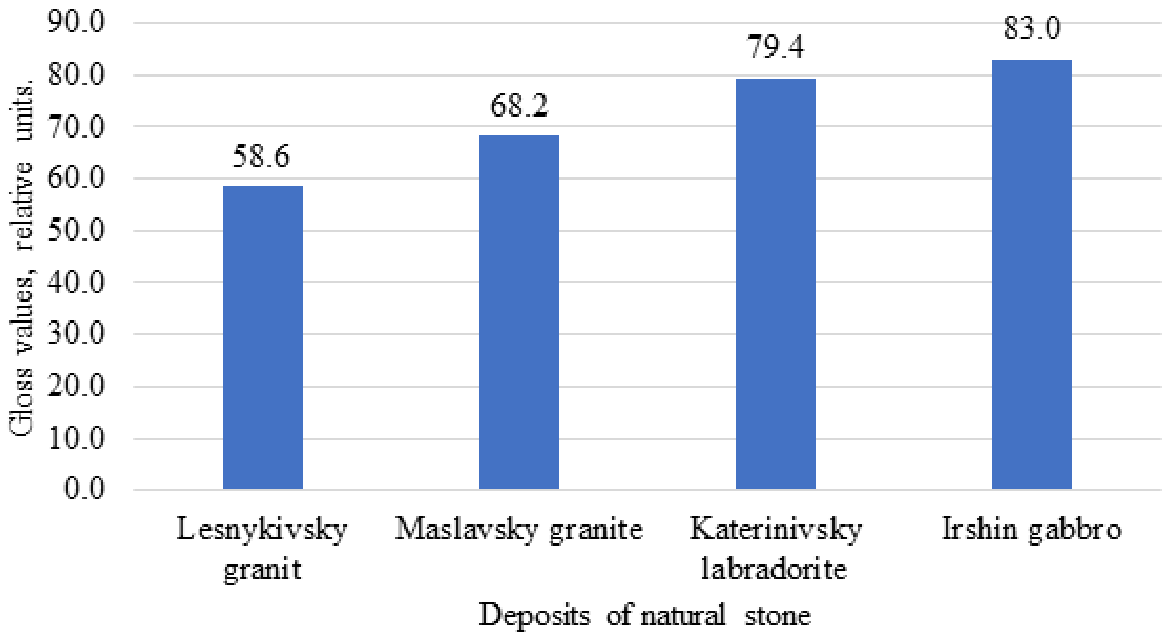

Figure 1. The gloss values of polished facing surfaces of samples of natural stone that have not been subjected to heating (zero point).

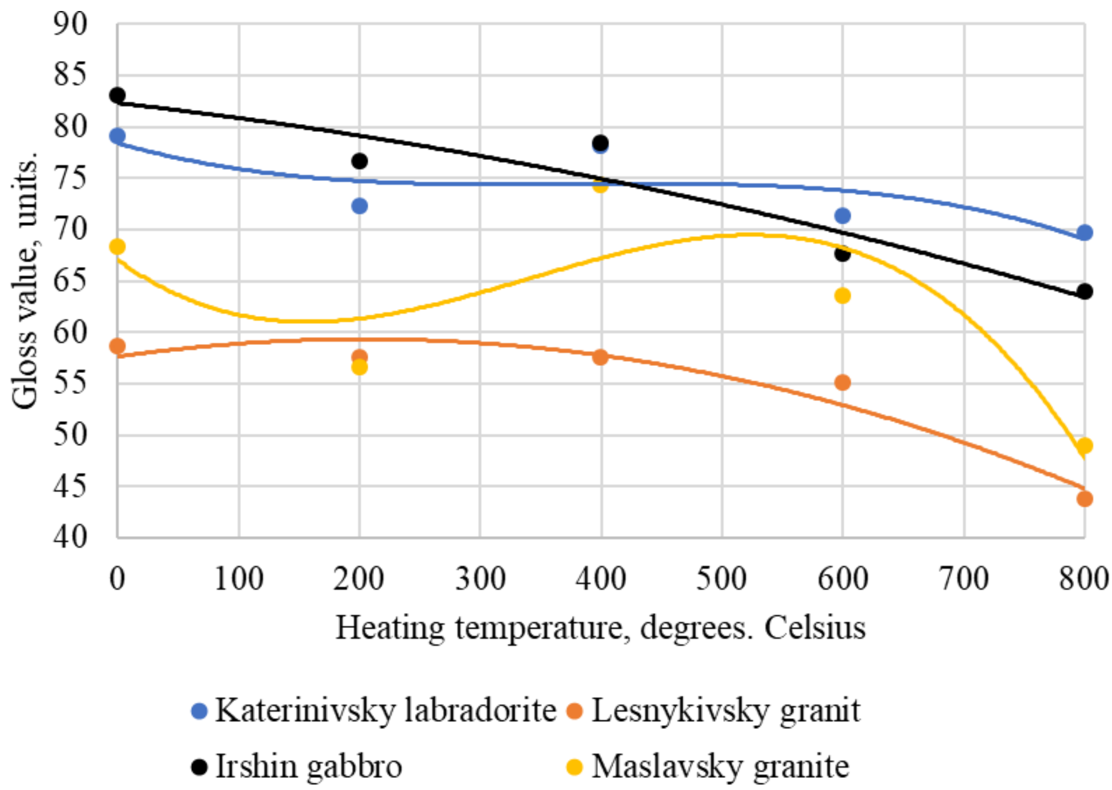

Figure 2. The dependence of the change in shine of the polished surface of natural stone on the heating temperature.

and basic types of natural stone samples depending on the intensity of their heating (figure 2).

The analytically derived relationships are described by polynomial dependencies of the 2nd and 3rd order.

Leznakyivsky granite:

$$S = -4 \times 10^{-5}t^2 + 0.0166t + 57.64, \quad (1)$$

where S is the surface luster value of the natural stone, unitless; t is the temperature of heating the natural stone, degrees Celsius.

Maslavsky granite:

$$S = -3 \times 10^{-7}t^3 + 0.0004t^2 + 0.0851t + 67.045. \quad (2)$$

Katerinivsky labradorite:

$$S = -8 \times 10^{-8}t^3 + 9 \times 10^{-5}t^2 + 0.033t + 78.389. \quad (3)$$

Irshynske gabbro:

$$S = -1 \times 10^{-5}t^2 + 0.0133t + 82.31. \quad (4)$$

During the investigation of the luster of polished surfaces of Labradorite samples, it was observed that at a temperature of 200 °C, there is a decrease in luster values in samples from the Katerynivske deposit of Labradorite (figure 2). At a temperature of 400 °C, there is an increase in luster values, followed by further decrease, and this process continues until a temperature of 800 °C. A similar trend is observed in samples of Irshynske gabbro.

The decrease in luster values of the polished surface of Labradorite samples at a temperature of 200 °C is explained by the onset of the breakdown of the mineral composition of Labradorite. Heating minerals induces the diffusion of atoms and molecules, leading to a change in their crystalline structure. In Labradorite and gabbro, the main minerals are plagioclase and Labradorite. Upon heating, plagioclases begin to decompose into orthoclase and anorthite. This process is accompanied by the release of free liquid, which disturbs the surface of the sample and reduces its luster.

The increase in luster values at a temperature of 400 °C is explained by the restoration of the crystalline structure of Labradorite. With further heating, the breakdown of the mineral composition continues, leading to a decrease in luster values.

Detailed explanation of each stage:

- 0 °C – Initial state of the sample, the crystalline structure of minerals is not disturbed, high luster.
- 200 °C – Initiation of the breakdown of the mineral composition, liquid is released, disturbing the surface of the sample, luster decreases.
- 400 °C – Restoration of the crystalline structure of minerals, increased luster.
- 600 °C – Continued breakdown of the mineral composition, luster decreases.
- 800 °C – Maximum level of breakdown of the mineral composition, minimal luster.

When heating Leznakyivsky granite to 200 °C, the luster decreased from 58.6 units to 57.5 units. Upon heating to 400 °C, the luster value almost did not change and remained at 57.4 units. Heating the granite samples to 600 °C resulted in a decrease in luster to 55.1 units, and at 800 °C, the luster value became 44 units.

The decrease in luster values of the polished surface of Leznakyivsky granite samples at 200 °C is explained by the initiation of the breakdown of the granite's mineral composition. Heating minerals induces the diffusion of atoms and molecules, leading to a change in their crystalline structure. In granite, the main minerals are feldspar, quartz, biotite, and amphibole.

Upon heating, feldspar begins to decompose into orthoclase and anorthite. This process is accompanied by the release of free liquid, which disturbs the surface of the sample and reduces its luster.

The almost unchanged luster value at 400 °C (57.4 units) may indicate that at this temperature, chemical and physical changes in the granite do not significantly affect its optical properties.

The decrease in luster at 600 °C (55.1 units) and 800 °C (44 units) may be associated with changes in the crystalline structure of minerals, such as deformation, decomposition, or phase transformation.

It is worth noting separately that Leznakyivsky granite contains a significant amount of feldspar, which is the most heat-resistant mineral. Therefore, the decrease in the granite's luster occurs more slowly than in Labradorite, where the main mineral is plagioclase, which is more prone to breakdown when heated.

When heating Maslavsky granite to 200 °C, the luster decreased from 68.2 units to 56.6 units. Upon further heating to 400 °C, the luster, on the contrary, increased and even exceeded the initial values of the unheated sample, reaching 74 units. With further heating, the luster decreased at 600 °C (63.5 units) and 800 °C (49 units).

The decrease in luster values of the polished surface of Maslavsky granite samples at 200 °C is explained by the initiation of the breakdown of the granite's mineral composition. Heating minerals induces the diffusion of atoms and molecules, leading to a change in their crystalline structure. In granite, the main minerals are microcline, plagioclase, quartz, biotite, and hornblende. Upon heating, microcline begins to decompose into microcline and albite. This process is accompanied by the release of free liquid, which disturbs the surface of the sample and reduces its luster.

The increase in luster values at 400 °C is explained by the restoration of the crystalline structure of granite. At this temperature, there is also some removal of free liquid from the sample surface, contributing to the increase in luster. Crystallization of microcline into more stable forms occurs at this temperature, improving the surface structure of the sample and increasing its luster.

The decrease in luster values at 600 °C and above is explained by further breakdown of the mineral composition of granite. This leads to the destruction of quartz, biotite, and hornblende, resulting in a deterioration of the surface structure of the sample and a decrease in its luster.

In conclusion, the changes in the luster of the polished surface of Maslavsky granite samples during heating can be explained by the following factors:

- Decomposition of microcline into albite and liquid at 200 °C.
- Restoration of the crystalline structure of microcline at 400 °C.
- Crystallization of microcline into more stable forms at 400 °C.
- Breakdown of quartz, biotite, and hornblende at 600 °C and above.

When heating natural stone to 800 °C, the greatest decrease in the luster of the polished surface of natural stone occurred in Irshynske gabbro – 23.7% (figure 3), and the least in Katerinivsky labradorite – 12.1%. Labradorite showed little change in its luster when heated. The average reduction in luster values was observed in Leznakyivsky and Maslavsky granites, at 21.3% and 18.5%, respectively.

The greatest decrease in luster on the polished surface of natural stone when heated to 800 °C in Irshynske gabbro is explained by the fact that the main mineral in gabbro is pyroxene, which is the most susceptible to breakdown when heated. At a temperature of 200 °C, pyroxene begins to melt, and at temperatures of 600 °C and above, it completely breaks down. This leads to a deterioration of the surface structure of the sample and a decrease in its luster.

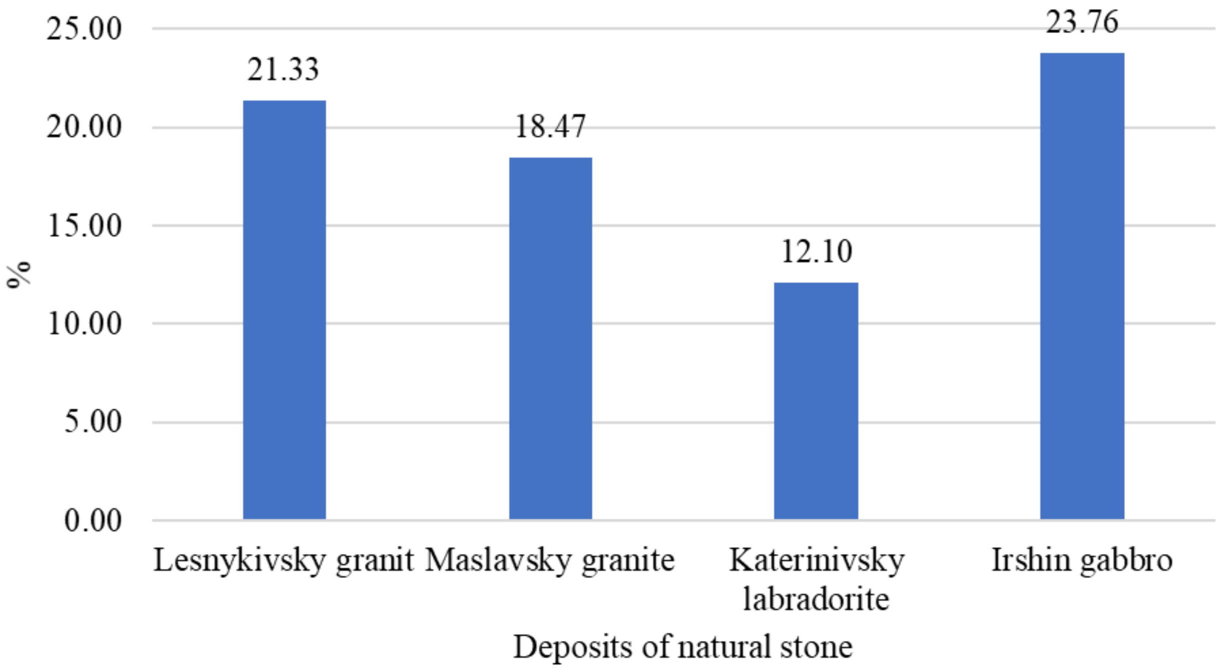

Figure 3. The magnitude of the decrease in the intensity of luster on the polished surface of natural stone after heating to 800 °C.

The least decrease in luster on the polished surface of natural stone when heated to 800 °C in Katerinivsky labradorite can be explained by the fact that the main mineral in labradorite is plagioclase, which is more resistant to heating than pyroxene. At a temperature of 200 °C, plagioclase begins to decompose into feldspar and anorthite, but this process is not accompanied by the release of liquid that would disturb the surface of the sample. At a temperature of 400 °C, there is some restoration of the crystalline structure of plagioclase, which also contributes to the increase in luster.

The average reduction in luster in Lesnykivsky and Maslavsky granites is explained by the fact that these granites primarily consist of feldspar and quartz, which have moderate resistance to heating. At a temperature of 200 °C, feldspar begins to decompose into feldspar and anorthite, while quartz may partially melt. At temperatures of 600 °C and above, the breakdown of quartz and feldspar occurs, leading to a reduction in luster.

During the heating of labradorite under atmospheric pressure, chemical reactions and transformations of the internal structure of minerals take place. The main processes include phase transition and oxidation of minerals, especially those containing iron. For example, in study [5], changes in the physical characteristics of granite under the influence of temperature due to the phase transition of quartz, which occurs at 573 °C under atmospheric pressure, are discussed. Unlike granite, labradorite does not contain quartz, so the oxidation of Fe in pyroxenes is the main source of changes in the physical and mechanical properties of labradorites at temperatures above 600 °C. Microscopic studies [3] confirm that high temperatures promote oxidation of gabbro specimens. It turns out that 600 °C is a threshold for the onset of mineral oxidation under atmospheric pressure, starting with a thin coating around pyroxenes.

With increasing temperature, oxidation develops on other crystals. At a temperature of about 800 °C, minerals containing $Fe2+$ inclusions undergo oxidation. Oxidized plagioclases appear as reddish spots on the surface. Gabbro and labradorites are among the primary rocks and contain 55–98% plagioclase. Therefore, similar processes are observed in labradorite specimens during heating. However, studies show that the oxidation of minerals, visually observed on all labradorite specimens, begins at a temperature of 300 °C.

4. Conclusion

The decrease in the luster indices of the polished surface of labradorite specimens at a temperature of 200 °C is explained by the initiation of the breakdown of the mineral composition of labradorite.

The increase in luster indices at a temperature of 400 °C is explained by the restoration of the crystalline structure of natural stone specimens.

The decrease in luster at 600 °C (55.1 units) and 800 °C (44 units) may be associated with changes in the crystalline structure of minerals, such as deformation, decomposition, or phase transformation.

The most significant reduction in luster of the polished surface of natural stone at 800 °C in Irshynsky gabbro is explained by the fact that the primary mineral in gabbro is pyroxene, which is the most susceptible to degradation when heated.

The least reduction in luster of the polished surface of natural stone at 800 °C in Katerynivsky labradorite can be explained by the fact that the primary mineral in labradorite is plagioclase, which is more resistant to heating than pyroxene.

At a temperature of about 800 °C, minerals containing $Fe2+$ inclusions undergo oxidation. Oxidized plagioclases appear as reddish spots on the surface. Gabbro and labradorites are among the primary rocks and contain 55–98% plagioclase. Therefore, similar processes are observed in labradorite specimens during heating. However, studies show that the oxidation of minerals, visually observed on all labradorite specimens, begins at a temperature of 300 °C.

Based on the obtained values, it is possible to predict changes in the luster intensity of the polished front surface of products made of basic and acidic natural stone after exposure to high temperatures. It also enables quality control of the front surface of natural stone products to obtain products with specified parameters for restoration or refurbishment works.

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Assessment of aesthetic and ecological functions of the urbanized part of small watercourses of Mlynivka and Radchanka by the indicator of visual quality of the environment

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Assessment of aesthetic and ecological functions of the urbanized part of small watercourses of Mlynivka and Radchanka by the indicator of visual quality of the environment

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Abstract. The article highlights the importance of protection and preservation of small rivers in the conditions of global urbanization, in the context of the study of the aesthetic value of the territory within urban and suburban landscapes. Since the preservation of small rivers is the primary goal for ensuring quality ecosystem services for the purpose of: recreation, functioning of the hydro-complex of the urban system, aesthetic purposes, such a study will allow to identify, at the initial stage, areas that have been significantly changed as a result of anthropogenic activity. One of the approaches to such a study is the assessment of the indicator of visual quality of the environment, which is the result of the summation of visual effects (visual pollution) inherent in urbanized areas within the shoreline of small watercourses. The study was conducted on the example of the small rivers Radchanka and Mlynivka within the limits of the Ivano-Frankivsk urban united territorial community. The main focus of the research was on identifying objects and factors that create visual pollution, according to 30 main criteria based on the proposed methodology, taking into account the elements of expert evaluation. To determine the contribution of each of the three groups of evaluated criteria – natural objects, anthropogenic and man-made objects, physiognomic characteristics of the territory, the method of calculating the relative indicator of the visual quality of the environment was applied. The result of the assessment was the identification of areas with high aesthetic value and areas that need to be restored to preserve natural aesthetic and ecological functions. The article contains proposals and solutions that can be recommended to communities to improve the visual quality of the territories within the shoreline of the mentioned watercourses.

1. Introduction

The protection and preservation of small watercourses is actualized in connection with global climate changes on a planetary scale. For Ukraine, in the conditions of war, such a task is complicated not only by the issues of revitalization and protection of rivers, but also by those issues that urgently arise before territorial communities in connection with the rapid pace of urbanization of territories that were not directly affected by military actions.

In such realities, urban planning solutions must be balanced in such a way that the natural conditions of the territories, in particular within the coastal lines of watercourses, are as close as possible to the original state, and natural river landscapes can provide aesthetic and ecological functions, within the limits of possible ecosystem services [1].

Among the scientific community in the field of environmental economics, urban planning, and experts in environmental protection, scientific research in the field of the potential of ecosystem services of small watercourses, rivers, and streams is being updated. Ecosystem services are defined as a set of functions and resources of ecosystems that ensure the preservation of the environment, create conditions for maintaining and improving human life.

Such an approach leads us away from the strict implementation of engineering and technical solutions and control of physico-chemical parameters of surface waters to a multifunctional approach, which aims to restore and preserve the river ecosystem, in particular, its aesthetic and ecological features and functions.

In order to increase the importance of protection and preservation of small rivers in the conditions of global urbanization, it is necessary to study the aesthetic value of the territory, one of the approaches to such a study is the assessment of the indicator of visual quality of the environment. This study reveals the importance of ecosystem services of small rivers and watercourses within urban and suburban landscapes.

2. Literature analysis and problem statement

In the Law of Ukraine "On the Nature Reserve Fund of Ukraine", Chapter 1, Art. 6 [2], the need to protect territories and objects of special aesthetic value, in addition to ecological or scientific value, is clearly highlighted. Instead, within urbanized territories, the Law of Ukraine "On the Improvement of Settlements" [3] Article 22 defines the need to improve the aesthetic appearance of the territories of cities or towns.

The legislation of Ukraine has a number of by-laws that determine the quality of the urban environment in terms of visual pollution and visual quality of the environment, in particular, DBN B.2.2-12:2019, DBN B.2.2-5:2011 with amendments, DBN B.2.2-41: 2019, DSP 173-96 with changes, DSP-145, where the need to apply planning decisions in harmony with natural landscapes and selection of dominant natural objects is indicated.

In the context of our research, the requirement prescribed in DBN B.2.4-3:2010, which determines the need to apply aesthetic requirements to structures located on the banks of watercourses in populated areas, is important [4].

There is significant progress in the scientific analysis of methodical approaches to solving the issue of assessing the aesthetic value of natural landscapes/complexes. In our opinion, approaches based on the methodology of Eringis and Budryunas [5] are extremely valuable, as well as Wöbse [6] and Kane [7].

In the studies [8–12] has accumulated sufficient theoretical and methodological experience for conducting such studies, which can be used to justify granting the status of a protected (reserved) territory depending on the aesthetic value and visual quality. Today, especially in conditions of altered natural landscapes as a result of military operations, such a value is extremely important.

The evaluation of the visual quality of the urbanized environment has a number of developments in the works [13–17], where various methods are applied, from surveying local residents to calculating coefficient of video-ecological receptivity of the territory. The assessment of the visual environment has already been carried out for some cities of Ukraine, in particular Lutsk, Rivne, Vinnytsia, Ivano-Frankivsk, Kharkiv, Dnipro, some districts of Kyiv [18–22].

From the analysis of the publications, we can see that the majority of research is focused either on the assessment of the visual (aesthetic) quality of natural landscapes or only on rural areas complicated by urbanization. Therefore, the question arises of the need to apply such an assessment for the suburban territory, which has aspects of both a natural and territorial complex, and an urban development of urban settlements with transport junctions, elements of improvement and engineering and technical construction solutions.

3. Purpose and objectives of the study

The purpose of the study was to assess the visual impacts inherent in urbanized areas within the shoreline of small watercourses, using the example of the small rivers Radchanka and Mlynivka within the limits of the Ivano-Frankivsk urban united territorial community. Since the preservation of small rivers within cities is the primary goal for ensuring quality ecosystem services for the purpose of: recreation, functioning of the urban water complex, aesthetic purposes, such an assessment will allow identifying, at the initial stage of research, areas that have been significantly changed due to anthropogenic activity and areas, where natural factors do not have a sufficient compensatory effect.

The authors of the study set the following tasks:

(i) Conduct an assessment of visual impacts in the urbanized area within the coastal line of small water streams, using the example of the small rivers Radchanka and Mlynivka within the Ivano-Frankivsk city united territorial community.

(ii) Identify, at the primary stage of the studies, areas that are significantly altered due to anthropogenic activity and areas where natural factors do not have sufficient compensatory impact, namely objects and factors that create visual pollution within the natural coastal line of the watercourse ecosystems.

(iii) Determine which groups of criteria (included in the list of assessment methodologies) have the most significant contribution to the visual quality indicator of the environment of Radchanka river and Mlynivka river and, accordingly, which zones along the coastal line have the most favorable conditions for restoration and recreation.

(iv) Provide suggestions regarding decisions that can be recommended to the communities for improving the visual quality of the territories within the coastal line of the mentioned small water streams.

4. Research methods

As part of the scientific project “Revival of the aesthetic and ecological functions of small watercourses of the Mlynivka (Stebnytska) and Radchanka rivers on the territory of the Ivano-Frankivsk City United Territorial Community”, an assessment of the visual effects along the shoreline of these watercourses was carried out. The assessment was carried out according to the protected scoring method [22] using the author’s software product “VisualEcoSafety” [23]. The formation of the matrix of points for statistical processing of data by groups of criteria was carried out in the Microsoft Excel environment, the elements of expert assessment were also used, the markings of observation points and images of watercourses were given using remote images in the Google Earth Pro program.

The visual impact evaluation scale contained 30 criteria, for a separate criterion the maximum score was 2 points, respectively, the observation point that is evaluated and is the most naturally and aesthetically attractive can receive 60 points. The gradation of the scale is distributed as follows: 0-20 points – we assess the visual impact as “satisfactory”, 21-40 points – “moderate” impact, 41-60 – visual impact is “acceptable”.

To assess the visual quality of the environment, 15 observation points were determined, which are evenly located on the research territory along the coastline of watercourses (figure 1).

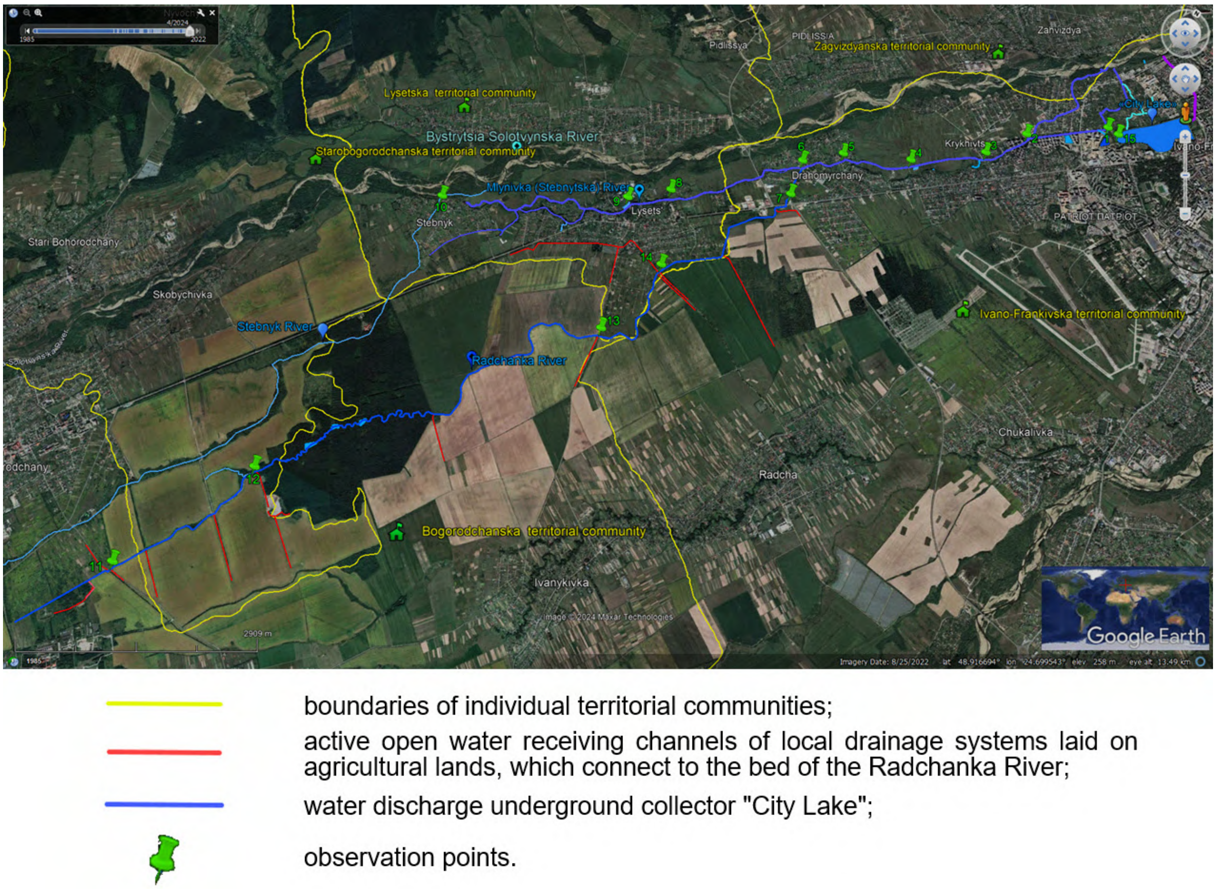


Figure 1. Location of visual impact assessment observation points along the coastline of the Mlynivka and Radchanka rivers.

4 experts were involved in the implementation of the project tasks, who conducted an impact assessment at the research site, this element of the expert assessment was used to avoid subjectivity. In order to obtain the evaluation results, the point evaluation was summed up for each criterion for each point for four experts separately, later the final result was averaged, in case the final score of one of the experts differed significantly (by more than 5 points) from the opinion of other experts, such final score was not the results of three or two experts were taken into account and averaged. The final final score can be identified as an indicator of the visual quality of the environment.

5. Research results

In the conditions of significant urbanization of agricultural areas, development with the creation of residential towns, “grabbing” of green zones and water protection zones of small watercourses for the arrangement of parking lots, expansion of the infrastructure of shopping areas, playgrounds, access roads, public transport stops, gas stations and solid waste storage areas , the use of advertising banners, pulsed lighting sources and electrical engineering objects, cellular communication objects, the visual environment of the city and suburban areas undergoes significant destruction.

We define the visual environment as the entire visible space of the environment perceived by the human eye, which is part of the environment. Accordingly, we consider visual pollution to be such pollution of the surrounding visible environment that distorts its natural (naturalistic) perception. The main elements of pollution include homogeneous and aggressive visual fields, man-made objects, as well as objects that increase elemental and destructive chaotic accumulation: solid waste, construction waste, power lines, lack of landscaping elements, green spaces, solid buildings and lack of open spaces , overpopulation of small areas, as well as the mass of objects that are not inherent in the natural environment. Visual pollution has the greatest negative impact on the state of a person's visual apparatus, nervous system and mental health. The human visual apparatus is significantly affected due to the uniformity of information (homogeneous visual fields) that enters the brain during binocular vision, as there are no dominant, natural and pleasant objects for perception, which in turn leads to discomfort and physiological disorders of visual functions, visual memory.

For example, the presence in the field of vision of the same gray buildings, a darkened environment with insufficient sunlight, in particular due to the closedness of spaces, especially in the non-vegetation period, since the vast majority of tree and shrub vegetation in cities belongs to November, causes a depressed and depressive mood, which identified as autumn or seasonal depression [24].

The overwhelming number of "visual pictures" that we observe outside our own home are advertising banners, gray buildings and an artificial environment that suppresses the emotional state and the nervous system. In particular, in the study [16], it is stated that visual pollution has such consequences for human health as: constant distraction, attention deficit syndrome, eye fatigue, reduction of diversity of thoughts, loss of goals and personal identity, stressogenicity and anxiety due to artificial landscapes, exhaustion, depression, rheumatic diseases, chaotic images reduce the ability of the brain to make clear and balanced decisions, especially in children. Dark, gray, subdued color combinations of the environment change the perception and psychological mood of a person.Currently, modern urban planning is faced with the problem of reducing the number of open green spaces, such as urban green zones and oases, in the form of parks, squares, coastal areas of rivers and lakes, urban botanical gardens, mini green spaces and local vertical gardening. The public and progressive representatives of city improvement departments are acutely concerned about the expansion of such green zones, the creation of green corridors between city districts and remote recreational facilities, the qualitative indicators of the visual environment of which are high. In addition, in the spring and summer, and with climate changes in the autumn periods, the need of citizens for the so-called recreational and rest green areas, which provide maximum visual contact with the natural objects of the environment, increases sharply.

Today, we observe a tendency towards a sharp increase and concentration of citizens in recreation parks and embankments of water bodies, especially on weekends. The recreational load is increasing sharply, accordingly, green areas cannot accommodate such a large number of people, the quality of the visual environment is sharply decreasing due to the excessive number of people.

Also, there is a problem of expanding access to aesthetically attractive natural territories that can provide a recreational function for residents of remote areas of the city, that is, to the possibility of ecological use of local territories in order to reduce the impact of visual pollution on citizens within the urban system, since a comfortable visual environment promotes health a person's health, his work capacity, improving his psychological state.

Since riverbed sections are not only located on the territory of the Ivano-Frankivsk City United Territorial Community, the research was expanded to include settlements located on the lands of Bogorodchanska, Starobogorodchanska, and Lysetska territorial communities. A detailed list of observation points, settlements, object links and coordinates are given in (table 1)
.

Table 1: List of observation points for assessment of the visual quality of the environment

No. of points	Name of the settlement	Street name	Object reference within the observation point	Name of the watercourse	Coordinates of the point
1	city Ivano-Frankivsk	Pryozerna Stefanyka Chornovola Tsentralna O. Girnyka Technical road Ivanikivska Radchanska-Poleva Mazepa	"Ozero" residential complex, sump, water inlet channel	Mlynivka river	48.912006^0 24.682422^0
2	city Ivano-Frankivsk	August 24	"Kalynova Sloboda" settlement, arch, pond	Mlynivka river	48.905830^0 24.669126^0
3	village Krykhivtsi	Vyvizna-Misyachna	Source, bridge	Mlynivka river	48.900705^0 24.663748^0
4	village Krykhivtsi	Sonyachna	"Bagno" tract, bridge made of connected pipes	Mlynivka river	48.894933^0 24.651787^0
5	Dragomyrchany village	Starotserkovna	Source, bridge	Mlynivka river	48.891447^0 24.639832^0
6	Dragomyrchany village	Shkilna-Nadrichna	Bridge, public transport stop	The mouth of the Radchanka River (confluence with the Mlynivka River)	48.887900^0 24.633667^0
7	Dragomyrchany village	Shkilna	Kolyba "Knaipa"	Radchanka river	48.882827^0 24.634903^0
8	Lysets urban-type settlement	Stefanyka	Wooden bridge	Mlynivka river	48.875849^0 24.614591^0
9	Lysets urban-type settlement	Chornovola	Pond on the river, stadium	Mlynivka river	48.872211^0 24.608244^0
10	Stebnyk village	Tsentralna	Object Bridge, Church of the Nativity of the Blessed Virgin Mary	Stebnyk river	48.860692^0 24.577381^0
11	Pohivka village	O. Girnyka	The river passes through a road pipe, agricultural fields, Bohorodchany LFGD in the distance	Radchanka river	48.804330^0 24.566940^0
12	Lands of Staro-Bohorodchansk	Technical road	Mochary tract, landfill, hydraulic fracturing	Radchanka river	48.820868^0 24.577906^0
13	Lysets urban-type settlement	Ivanikivska	Reclamation fields	Radchanka river	48.855331^0 24.617179^0

No. of points	Name of the settlement	Street name	Object reference within the observation point	Name of the watercourse	Coordinates of the point
14	Lysets urban-type settlement	Radchanska-Polova	Bridge near the hospital	Radchanka river	48.866231^0 24.620559^0
15	city Ivano-Frankivsk	Mazepy	City lake, canal outlet to the city lake	City lake	48.911703^0 24.684721^0

The results of the evaluation of the visual effects of the above observation points are distributed as follows (figure 2). Point 12, located on the lands of the Starobogorodchansk Territorial Community, received the lowest visual quality of the environment (figure 3). The territory is designated for a solid waste landfill, contains a gas distribution station, the access roads are complicated and eroded, the designated communications are covered with corrosion, the physiognomic characteristics of the territory are mainly of anthropogenic origin, the visual impact is satisfactory.

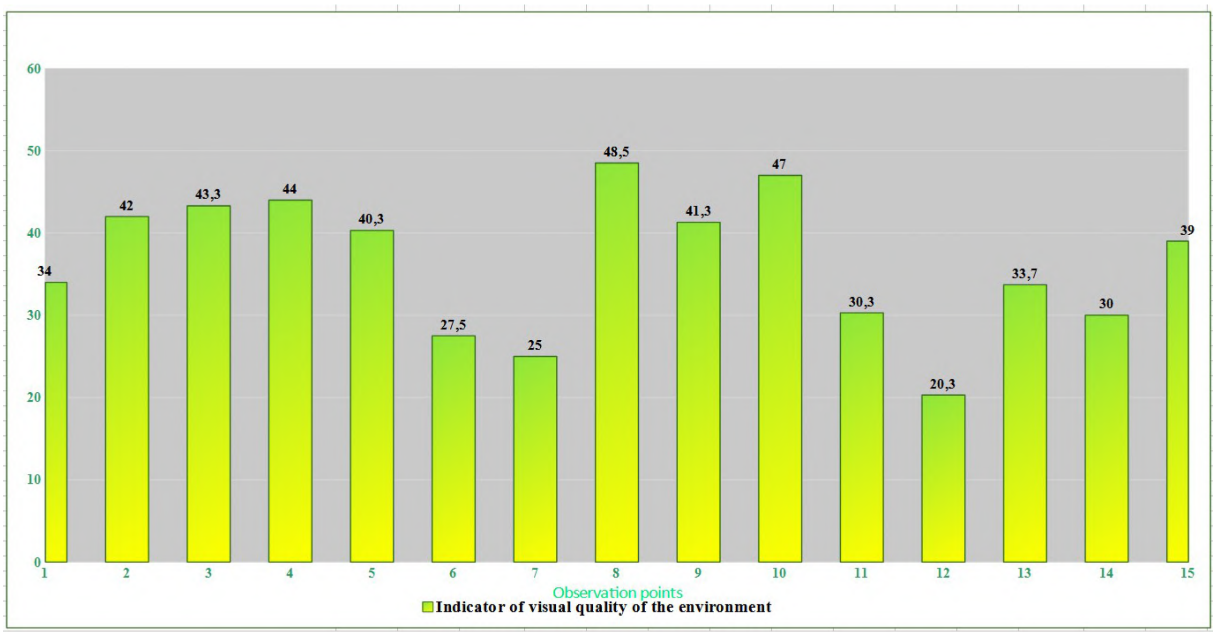
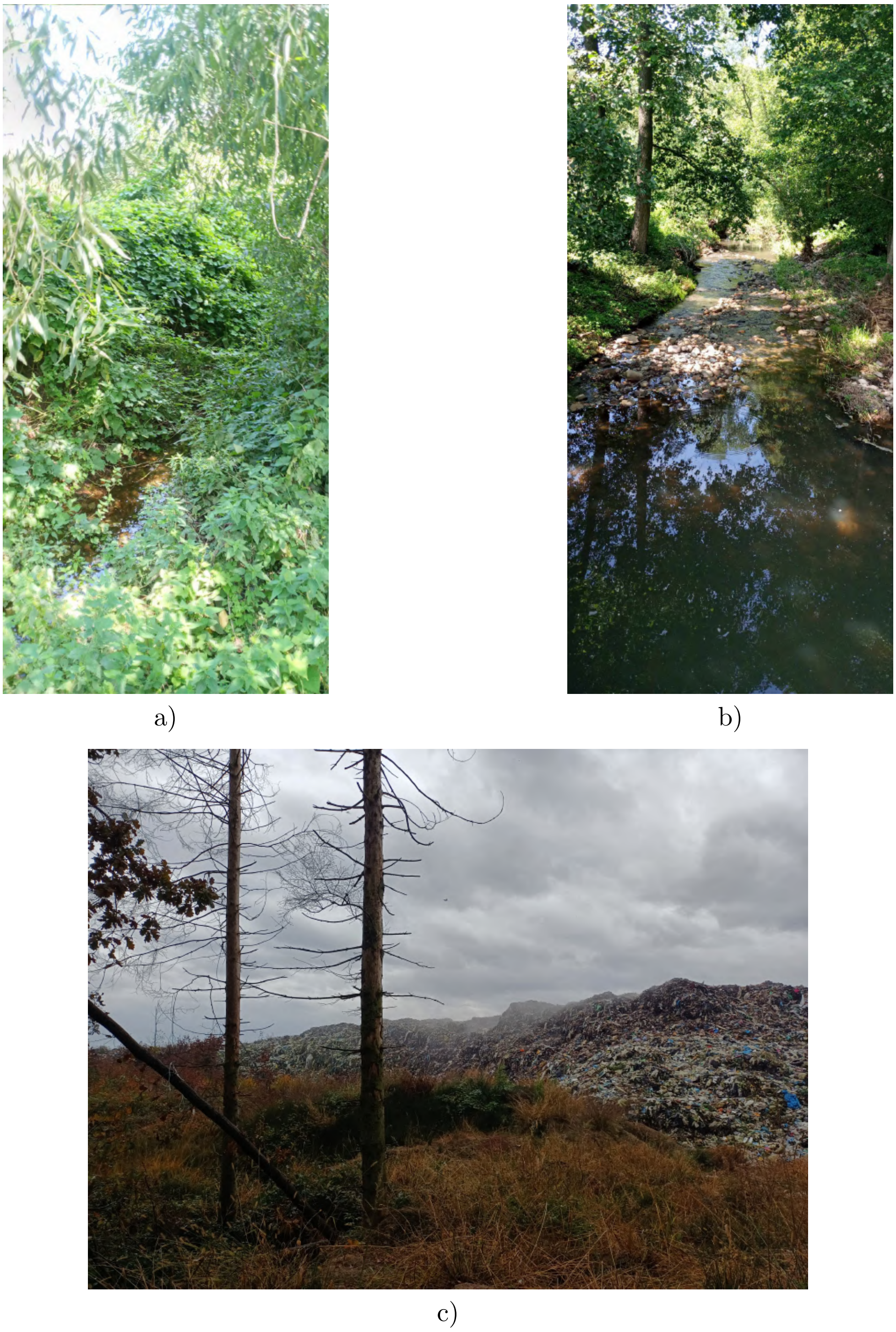


Figure 2. The results of the assessment of the indicator of visual quality of the environment along the coastline of the Mlynivka and Radchanka rivers.

Research points 6 and 7 are located within the village. Dragomyr residents received 27.5 and 25 points, which corresponds to a moderate visual impact. Despite the presence of a small watercourse, the coastline is overloaded with anthropogenic objects – the extreme proximity of an asphalt road to the watercourse, an unfortunate combination of a children's playground and a public transport stop, which can cause lubricants and gasoline to flow into the riverbed during rainy periods, the location of a commercial trailer with external storage of construction materials materials, the location of the bio-toilet opposite the site of the public catering establishment (kolyba), etc.

The highest points of the visual quality of the environment were obtained by 8 and 10 observation points (figure 3), located in the village of Lysets et al. Stem respectively. The extremely high potential for the development of ecological and aesthetic functions of the research area is reflected in the dominant objects in the village. Lysets on the Mlynivka River, the



a) b)

c)

Figure 3. Photo-fixation of observation points with the highest and minimum points of the indicator of visual quality of the environment (a) – 8 observation point, territory of the village. Lysets, Mlynivka River; b) – 10 observation point, territory of the village. Stebnyk, river Stebnyk; c) – 12 observation point, land of Starobogorodchansk Territorial Community, solid waste landfill near the Radchanka River).

natural coastline with its inherent ecosystem of vegetation is perfectly preserved, perennial woody vegetation was present in the study area, the meandering of the channel flow was clearly expressed, visually assessed water quality indicators were high, the territory was equipped with small architectural forms made of natural materials – trees yan motyk, cult buildings are present as objects of cultural and historical value, the territory has not changed much, the physiognomic characteristics of the territory are of natural origin.

Research points 2, 3, 4, 9 are located in the city of Ivano-Frankivsk, the village of Kryhivka and the village of Foxes also correspond, according to the results of the assessment, to an acceptable visual impact, and have the potential of high visual quality of the environment.

Moderate visual impact corresponds to points 1, 5, 6, 7, 11, 13, 14, 15 of the shoreline of the Mlynivka River and the Radchanka River with the outlet of the water flow to the city lake in the city of Ivano-Frankivsk.

To determine the contribution of each of the three groups of evaluated criteria – natural objects, anthropogenic and man-made objects, physiognomic characteristics of the territory, the method of calculating the relative indicator of the visual quality of the environment was applied. For this purpose, the points assigned by the experts, received in each of the criteria groups, were summed up, averaged and divided by the number of criteria contained in the group. As a result, we received an indicator reflected by a certain group of criteria. Since the maximum relative indicator can correspond only to the 2nd, we can analyze according to the given diagram (figure 4) which of the groups of criteria makes the greatest contribution to the indicator of the visual quality of the environment and in which territories the visual quality can be improved relative to the point area of observations.

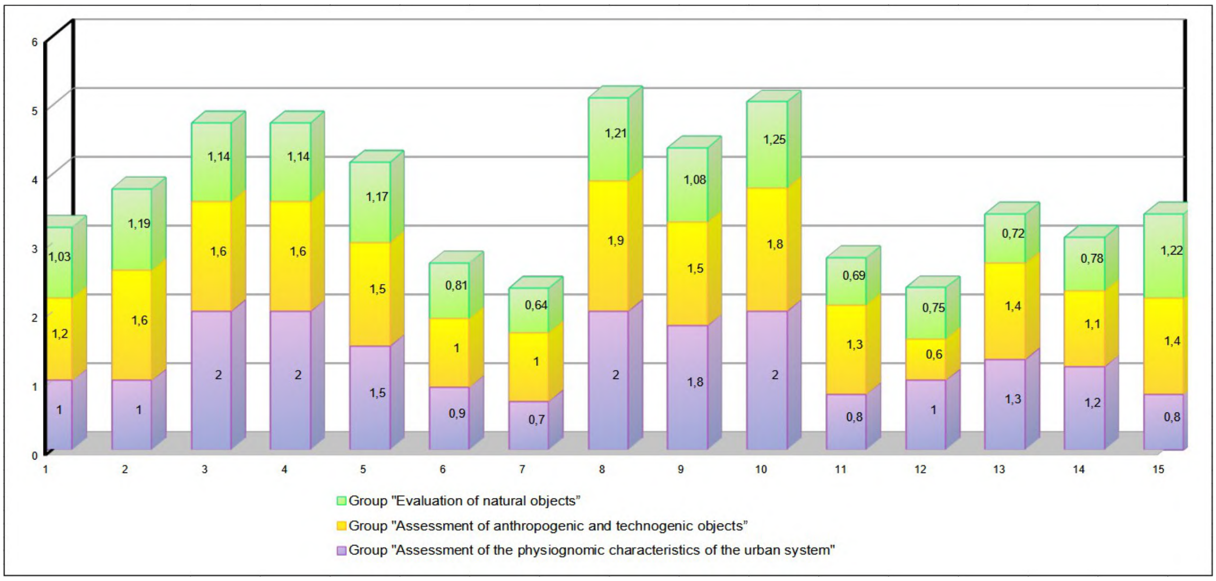


Figure 4. General distribution of the relative indicator of the visual quality of the environment by groups of criteria at observation points.

According to the group "Evaluation of natural objects (general impression of the territory being evaluated)", more than half of the criteria in this group are clearly reflected in the research territory, in particular – the color of the territory, the formed coastal zone, the presence and meandering of rivers, the mixture and diversity of the state of forest stands, striking dominants of natural origin stand out, the naturalness of the territory is ensured at 1, 2, 3, 4, 5, 8, 9, 10, 15 observation points. The maximum naturalness among the specified points is presented in 10 and 15 points, although the highest overall score of visual quality was 8 point.

According to the group "Assessment of anthropogenic and technogenic objects (diversity and expediency of anthropogenic objects)", more than half of the criteria in this group are absent and not reflected in the research area, in particular – urbanization, chaos, the presence of advertising banners, places for collecting solid waste, which is in sight, the territory is little changed by human activity, combined with natural objects, agricultural fields are absent or combined with one-story residential buildings, large-scale engineering structures are not visually noticeable, there is a sufficient number of visually pleasing objects with a variety of elements. This visual situation is reflected in 1, 2, 3, 4, 5, 8, 9, 10, 11, 13, 14, 15 observation points. Observation points 6 and 7 were overloaded with anthropogenic objects, which was analyzed above, at observation point 12 there is a garbage dump, which sharply worsens the indicators of the visual quality of the environment, despite the presence of a forest strip and a watercourse in the field of vision.According to the group "Assessment of the physiognomic characteristics of the urban system", the maximum naturalness of smells and sounds of nature is reflected in points 3, 4, 8, 10, which also have the highest indicators of the visual quality of the environment (figure 2).

In points 1, 2, 5, 9, 12, 13, 14, more than half of the criteria reflect a combination of smells of natural and anthropogenic origin and quiet single sounds of technogenic origin. The moderate situation in this group of criteria is reflected in points 6, 7 located in the village. Dragomyrchany is near the road, which worsens the acoustic and physiognomic situation of the territory. At point 11 in the village In the course of the investigation, a spill of lubricants was recorded near the dirt road, which caused a strong toxic smell over a large area. Point 15, this area of the Ivano-Frankivsk city lake is oversaturated with the number of vacationers who create noise of anthropogenic origin, there is also a skate park nearby, a parking lot of the "Reinkarts" hotel with active car parking, which causes sharp sounds and smells from the operation of car engines.

6. Discussion of the results

In order to reduce visual pollution and increase the visual quality of the environment on the territory of the channel sections of the Mlynivka (Stebnytska) and Radchanka rivers within the To the Ivano-Frankivsk City United Territorial Community, Bogorodchanska, Starobogorodchanska, Lysetska territorial communities, it is necessary to implement specific planning decisions regarding urbanized territories, and within the boundaries of natural (unspoiled) areas, the principle of non-interference should be observed as much as possible, which will correspond to the preservation of the aesthetic value and visual comfort of the environment.

The analysis of literary and scientific sources showed sufficient experience from developments in domestic and foreign practice, the support of such decisions is substantiated by the application of a number of legislative acts and state building regulations. We hope that soon the domestic environmental protection legislation will be adapted to the legislation of the European Union and will contribute to the approval of the Law of Ukraine "On the territories of the Emerald Network", which would outline the value of such territories not only in terms of biodiversity, but would also be supplemented by the criterion of visual/aesthetic quality of the set of natural factors, that form the territories and corridors of the Emerald Network. In our opinion, such an addition would be a clear argument for the introduction of protective status.

7. Conclusions

(i) Based on studies of visual impacts along the riverbanks of Mlynivka and Radchanka, it has been found that the lowest level of visual quality of the environment is observed at point 12 in the Starobohorodchanska community. The highest indicators of visual quality were recorded at points 8 and 10, located in Lysets and Stebnyk respectively. Specifically, in Lysets, there is a high potential for the development of ecological and aesthetic functions with a beautifully preserved natural shoreline, well-expressed meandering of the channel, and high water quality. Other points are characterized by moderate visual impact.

(ii) Analysis of visual pollution of natural riverbanks in the Starobohorodchanska territorial community and the village of Dragomyrchany revealed significant anthropogenic interference. The presence of a solid household waste landfill, eroded paths, corroded communications, and the proximity of asphalt roads to the water streams increase the risks of pollution and negatively affect the visual attractiveness of these landscapes.

(iii) Research on visual, anthropogenic, and physiognomic characteristics of urban systems along the rivers Mlynivka and Radchanka demonstrates significant differences between selected points. Evaluation of natural objects showed high naturalness at points 10 and 15, but the overall score for visual quality is highest at point 8. In the context of anthropogenic objects, points 6 and 7 were found to be overloaded, while at point 12, the presence of a landfill negatively affects visual quality. Physiognomic characteristics of the urban system revealed maximum naturalness of smells and sounds of nature at several points, however, point 15 suffers from noise of anthropogenic origin due to a large number of vacationers and cars. Overall, the results of the study will contribute to the expansion of natural zones and revitalization of rivers, enhancing ecological safety and the role of ecosystem functions in local communities.

(iv) To improve the visual quality of the environment within the studied areas, we can provide the following suggestions:

- Make changes to the local normative acts regulating the implementation of measures for the improvement of the territories of Ivano-Frankivsk, Lysets, and Starobogorodchansk communities, emphasizing the need to minimally change the natural river landscape complexes, thus improving the visual natural environment.
- Inform the public of the specified territories about the causes of visual pollution and its possible consequences for the environment and the health of the population, especially children. Formation of the importance of the habit of a healthy visual (visual) environment.
- To recommend local communities to carry out regular measures to clean and organize the coastline of Mlynivka, Radchanka, and Stebnyk watercourses, combining them with eco-educational actions.
- To the Ivano-Frankivsk City United Territorial Community to recommend the expansion of recreational areas due to the development of ecological trails, historical reconstructions along the Radchanka and Mlynivka rivers, to equip sources of drinking water that come to the surface on the territory of Krykhivtsi and Dragomyrchany villages. Such solutions will reduce the recreational load on the city lake and recreation park on weekends and holidays.
- The Starobohorodchansk community to initiate design decisions regarding the possibility of reducing the area of the solid waste landfill, using modern approaches to the household waste management system in accordance with the provisions of the Law of Ukraine "On Waste Management" No. 2320-IX dated March 31, 2023.
- Reduce the use of advertising banners, set up container sites for the collection of solid waste, in specially designated places, with the limitation of getting into the field of vision in open spaces, change the color of painting large-scale electrical engineering objects (power lines, distribution stations) from black to gray-blue, as an example of the application of such practice in the territory of the Republic of Poland.
- Reducing the influence of aggressive and homogeneous visual fields due to the use of environmentally acceptable solutions: changes in color scheme, visual separation of territorially large-scale objects using the principles of landscape design. Although the degree of natural areas and green spaces within the research area is sufficient, it is recommended

to use vertical and horizontal greening within the population centers of the city of Ivano-Frankivsk (town "Kalynova Sloboda", housing complex "Ozero", "Millennium") and suburban territory with Krykhivtsi, Dragomyrchany village. Such solutions will form dominant, natural, visually pleasing greening centers, especially during the growing season.

The analysis of scientific interest and research in this area shows the need to create a separate regulatory document that would highlight standardized methodological approaches to the assessment of visual pollution and permissible levels of impact, would regulate the application of regulatory decisions in the territories of communities, since the issue of assessing the impact of visual pollution in the field of environmental safety is no less important than the assessment of the effects of other polluting factors.

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The issues of technological modeling of physicochemical iron removal from deep groundwater at the rapid filter

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Abstract. An exact solution to the task of physicochemical iron removal from natural water containing excess iron ferric form at the rapid filters is presented in the article. The principles of applied optimization of filters for iron removal are formulated based on technical and economic calculations. Three filter control algorithms are described and technological modeling of its operation is performed throughout the service life of the filter medium when implementing a regular algorithm. The impact of the main design parameter on the economic indicators and, first of all, the reduced costs is analyzed. The possibility of minimizing the cost of water treatment through a reasonable choice of the packed bed height has been demonstrated.

1. Introduction

The existence of humanity is directly related to the use of water resources, and the key to the progressive development of society is their frugal use [1, 2]. Human health is largely determined by the quality of consumed water [3, 4]. The natural water sources are recommended to use that most closely meet the requirements for drinking water [5,6]. The ground interlayer waters belong primarily to such sources [7,8]. Quite often, the deep groundwater contains a high concentration of iron and requires special treatment [9]. Different methods of iron removal from water have been developed, which have their own technical and economic limits of use [10–14]. The method of contact iron removal from groundwater has become widespread in Ukraine [5,15]. It provides the previous degassing and aeration preparation and filtration at rapid filters.

The assessment of the functionality of specialized filters for iron removal and their treatment potential, is more difficult than that of clarifier filters, since it is necessary to monitor the development of the physicochemical situation in their medium throughout a numerous sequence of filter runs [5, 16]. These conditions are unique during each filter run due to the inevitable increase in the amount of non-washable deposit based on iron hydroxide [15,17,18]. Not only the quality of the treatment, the losses of mechanical energy but also the composition of the solid phase have to be constantly monitored in practice now. It is much easier and cheaper to carry out such control using mathematical modeling methods [19, 20]. Therefore, a special approach is required to calculate the filtration of water with a high concentration of iron compounds, providing for a quantitative analysis of the complex of processes in the filter medium throughout both a separate operating period and the entire time of its effective operation.

The technological optimization procedure usually used at rapid filters is based on two efficiency criteria when separating aqueous suspensions for different rate modes [21]. In relation to the filtration mode with a constant rate, the specified criteria are formalized in the form of relationships between the contamination concentration of in the filtrate, head losses in the packed bed and their standard values. These criteria express the restrictions in symbolic form that must be imposed on the function of filters as clarifiers. Their compliance should be constantly monitored.

However, such an approach is insufficient for technological optimization of physicochemical iron removal, since it helps to reduce only operating costs. Indeed, capital costs while playing a special role in the economic analysis of the filter operation are not actually taken into consideration. As a result, it is necessary to conduct full-scale mathematical and technological modeling of the operation of such filters in order to minimize the cost of deep groundwater treatment. So, it is necessary to analyse in detail changes in filtration characteristics (output concentration of total iron C_e, head losses in the operation bed Δh, filtration rate V) over at least the entire service life of the packed bed (total time of productive operation of the filter with one change of medium T_f).

2. Theoretical analysis of physicochemical iron removal

The fundamental mathematical model of the physicochemical iron removal from deep groundwater using a rapid filter was developed based on the results of our own experimental studies of the technological process in laboratory and industrial conditions and the conceptual model [15]. Its formulation as a system of three interconnected compartments (ferrous iron, ferric iron, and hydraulic), as well as a rigorous solution in a complex integral form, are presented in [22]. In the article, the variables and parameters with a dash above are dimensionless. The dependencies shown below make it possible to predict spatiotemporal changes in the most important filtration characteristics for the particular case when the processes of removing ferrous iron and ferric iron Fe substances occur independently of each other for the relative volumetric concentrations of iron oxide in dissolved $(\overline{C}_h)$ and deposited $(\overline{S}_h)$ forms

$$\overline{C}_h\left(\overline{z},\overline{t}\right)=\frac{\overline{C}_{h0}\overline{C}_h^0\left(\overline{z}\right)}{\overline{C}_h^0\left(\overline{z}\right)+\left[\overline{C}_{h0}-\overline{C}_h^0\left(\overline{z}\right)\right]e^{-\overline{k}_h\overline{C}_{h0}\overline{t}}},\tag{1}$$

$$\overline{S}_h\left(\overline{z},\overline{t}\right)=1-\frac{\overline{C}_{h0}\left(1-\overline{S}_h^0\right)e^{-\overline{k}_h\overline{C}_{h0}\overline{t}}}{\overline{C}_h^0\left(\overline{z}\right)+\left[\overline{C}_{h0}-\overline{C}_h^0(\overline{z})\right]e^{-\overline{k}_h\overline{C}_{h0}\overline{t}}}.\tag{2}$$

Where $\overline{C}_{h0}$ is the inlet volumetric concentration of iron oxide; $\overline{S}_h^0$ is the constant regardless of height (due to intensive mixing of the filtering material during washout) relative initial volumetric concentration of the deposited iron hydroxide; $\overline{k}_h$ is the relative reduced rate coefficient of the deposition of hydroxide particles; $\overline{t}$ is the filtration time; $\overline{C}_h^0\left(\overline{z}\right)$ is the relative distribution of dissolved hydroxide along the height of the packed bed after the first portion of water passes through it, which is described in the absence of ferrous iron by the expression

$$\overline{C}_h^0\left(\overline{z}\right)=\overline{C}_{h0}e^{1-\overline{k}_h\psi\left(\overline{S}_h^0\right)},\tag{3}$$

where $\psi=S_{mh}/\left(n_0C_0\right)$, $\overline{S}_h^0=S_h^0/S_{mh}$; S_{mh} is the dirt-holding capacity of the filter medium in relation to hydroxide particles; n_0 is the clean bed porosity; C_0 is the initial concentration of total iron in water. Then representations (1), (2) are transformed to the form

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$$\overline{C}_h\left(\overline{z},\overline{t}\right)=\frac{\overline{C}_{h0}}{1+\left(e^{\psi\overline{k}_h\overline{z}}-1\right)e^{-\overline{k}_h\overline{C}_{h0}\overline{t}}},\tag{4}$$

$$\overline{S}_h\left(\overline{z},\overline{t}\right)=1-\frac{1-\overline{S}_h^0}{1+\overline{C}_h^0\left(\overline{z}\right)\left(e^{\overline{k}_h\overline{C}_{h0}\overline{t}}-1\right)},\tag{5}$$

If the relative initial concentration of ferrous iron is $\overline{S}_f^0>0$, then the general expression is valid

$$\overline{C}_h^0\left(\overline{z}\right)=\overline{C}_{h0}e^{-\psi\overline{k}_h\left(1-\overline{S}_h^0\right)\overline{z}}+\frac{\overline{K}_d\overline{S}_f^0}{\psi\overline{k}_h\left(1-\overline{S}_h^0\right)}\left(1-e^{-\psi\overline{k}_h\left(1-\overline{S}_h^0\right)\overline{z}}\right).\tag{6}$$

The expression for $\overline{S}_h$, in particular (2), make it possible, if there is an empirical relationship between the specified concentration and the current hydraulic conductivity k, simply determine the relative head losses in the bed in case $V=$ "$const$". The corresponding formula is derived as a result of solving the hydraulic compartment [22]

$$\triangle\overline{h}\left(\overline{t}\right)=\frac{h\left(0,\overline{t}\right)-H_d}{H^0-H_d}=\int_0^1\frac{\mathrm{d}\overline{z}}{f_k\left(\overline{S}_h\left(\overline{z},\overline{t}\right)\right)},\tag{7}$$

where h is the piezometric head, H_d is the head at the bed outlet; f_k is the symbol of the normalized hydraulic conductivity function; H^0 is the head at the inlet to the clean filter medium at the constant filtration rate V.

3. Technical and economic analysis and choice of filter control algorithm

We set the control time T for a generalized economic analysis of filtration costs. It includes both productive (directly work of the filter) and non-productive (spent on all washouts) times. The basic equation for technical and economic analysis was taken in the following general form [23]

$$CC+CO=VT\Omega_fP_W,\tag{8}$$

where CC, OC are the capital and operating costs; Ω_f is the filter medium surface area; P_W is the cost per unit volume of the treated water.

$$\frac{LP_F}{VT_f}+\frac{N_T}{T}\frac{P_{BW}}{V\Omega_F}=P_W-\frac{\Delta CC+\Delta OC}{VT\Omega_F},\tag{9}$$

where L is the bed layer height; P_F is the cost of a unit volume of filtering material and the cost of its replacement; T_f is the service life of the bed material; N_T is the number of filter runs in the specified period; P_{BW} is the cost of one washout; ΔCC, ΔCC are all items of capital and operating costs with the exception of the costs of filtering material (automation equipment, pumps, aerators, etc.) and washout. The relative time is introduced to generalize the results of subsequent calculations, so that $\overline{T}_f=VT_f/\left(n_0L\right)$, $\overline{T}=VT/\left(n_0L\right)$. Then equation (9) will be

$$\frac{P_F}{\overline{T}_f}+\frac{N_T}{\overline{T}}\frac{P_{BW}}{L\Omega_F}=n_0\left(P_W-\frac{\Delta CC+\Delta OC}{\overline{T}L\Omega_F}\right),\tag{10}$$

In the case of the second (regular) algorithm ($t_{fj}=t_f$), equation (10) is transformed to

$$\frac{P_F}{\overline{T}_f}+\frac{P_{BW}}{L\Omega_F\overline{t}_f}=RC=n_0\left(P_W-\frac{\Delta CC+\Delta OC}{\overline{T}L\Omega_F}\right),\tag{11}$$

where RC is the reduced costs of the treated water. The main goal of a large extent of technical and economic calculations was a comparative analysis of three filter control algorithms, namely, irregular I (decreasing durations of filter runs t_{fj}, $j = 1, 2...N$), regular II (with a uniform calculation step, so that $t_{fj} = t_f$) and combined III (with sequences of filter runs I, II of identical durations, respectively t_{fI} and t_{fII} and besides $t_{fI} > t_{fII}$).

Particular attention was paid to algorithm II, which is widely used in practice due to its simple automation. In order to clearly establish the optimal interval t_f at which the reduced costs will be minimal when controlling the filter in accordance with algorithm II, it is necessary to calculate the dependence $RC\left(\bar{t}_f\right)$. Three graphs of this relationship, which correspond to the basic values Ψ_0 (the ratio of the contents of ferric iron and total iron in the initial water) and moderate contamination of the water supplied to the filter ($\overline{C}_0 = 1$), are shown in figure 1.

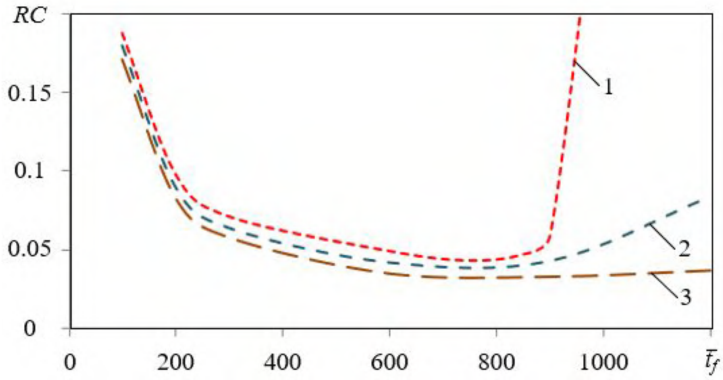

Figure 1. Dependence $RC\left(\bar{t}_f\right)$ at $\overline{C}_0 = 1$: $1 - \Psi_0 = 0$; $2 - \Psi_0 = 0.5$; $3 - \Psi_0 = 1$.

Based on that it is clear that the optimal relative value $\bar{t}_f$ is uniquely related to Ψ_0. Thus, in order to reduce the cost of the treated water to a minimum when using algorithm II, it is enough to specify the curve of the function $RC\left(\bar{t}_f\right)$ for a given initial ratio between the forms of iron. Approximate values of the required optima for $\bar{t}_f$ and RC correspond to the lowest point on this curve. In the case under consideration, three values $\bar{t}_f$ corresponding to the condition $RC = min$ were obtained, namely, $\bar{t}_f = 800$ at $\Psi_0 = 1$, $\bar{t}_f = 700$ at $\Psi_0 = 0.5$, $\bar{t}_f = 630$ at $\Psi_0 = 0$.

Logically, as $\overline{C}$ increases and Ψ_0 decreases, the range of practically acceptable values of $\bar{t}_f$ decreases. Finally, such a procedure for applied optimization of a technological process no longer makes sense if $\overline{C}_0 \geq 2.5$ and $\Psi_0 = 0$, since the filter here is generally not able to cope with such heavy contamination.

4. Applied optimization of design parameters

One of the effective ways to increase the efficiency of rapid filters for iron removal is a scientifically substantiated choice of their design parameters. The fundamental importance among them for the duration of filter runs and service life of filter medium, and as a result for the economics of iron removal are the height of the medium layer L and (equivalent) diameter of filter media grains d_g.

Particular attention in theoretical studies of the significance of the main design parameter was paid to the more unfavorable from the technological point of view limiting case, namely, the initial water (when fed directly to the filter) contains an excessive amount of iron only in the oxide form. Such type of groundwater contamination is real after its forced aeration, which, however, significantly increases the cost of water treatment. But the results of mathematical modeling obtained in this case allow us to get a clear idea of the greatest complications that can be encountered during physical-chemical iron removal in practice.

The recommendations on the rational control of the filter under such conditions, developed on their basis, will guarantee its effective work and, first of all, high quality of the filtrate in any situations encountered in practice, when iron is initially contained either only in the oxide form, or in both forms at an arbitrary ratio between them. Moreover, the value of such analysis also consists in the fact that it is easy to foresee and technically realize in the filter design the operative change of the bed height and thus to correct the filter operation at any stage.

Finally, the subject of the calculations was the evaluation of the sensitivity of the reduced costs in relation to the height L. The calculation interval for the argument L was limited to a minimum possible value (L_{min}) and a maximum value of 2 m. In fact, in this way the range of values L occured in existing filtration plants was fully covered. Then a new variable $\overline{L} = L/L_{min}$ was introduced and the calculation dependencies were transformed to single it out as an argument of the required functions. In particular, the formula for the relative output concentration of dissolved iron took the following form

$$\overline{C}_{he}\left(\widetilde{t}, \overline{L}\right) = \frac{\overline{C}_{h0}}{1 + \left(e^{\psi \overline{k}_h \overline{L}} - 1\right) e^{-\widetilde{k}_h \overline{C}_{h0} \widetilde{t}}}, \tag{12}$$

where $\widetilde{t} = \overline{L}\overline{t}$, $\widetilde{k}_h = \overline{k}_h/\overline{L}$.

The regular filter control algorithm was chosen as the most promising in practical terms (minimum automation costs), i.e. the duration of all filter runs during the bed service life was assumed to be the same. The most representative data of calculations are shown in the form of two sets of curves in figure 2 and figure 3. Figure 2 illustrates the dependencies $RC\left(L\right)$ at duration $t_f = 8$ hours and discretely varying water contamination C_0. All curves have a distinct minimum, which indicates the importance of a reasonable choice of L.

A similar conclusion follows from figure 3, where the above curves correspond to a single value C_0 and different durations of t_f. The indicated curves have similar features. First of all, we should note the existence of extremely small values of RC at strictly defined values of L. Moreover, the corresponding values L_{min} differ markedly at different values of t_f and C_0 (figure 2).

For this reason, it is very important for the preliminary selection of L to be based on the specific conditions and, above all, on the assumed value C_0 and the intended duration of t_f. Also noteworthy is the behavior of the calculated curves at low bed heights. Their asymptotic

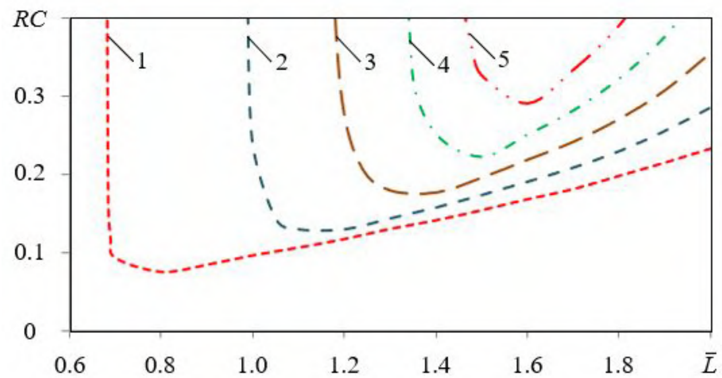

Figure 2. Dependence of reduced costs on packed bed height $\left(\overline{t}_f = 100\right)$: 1 – $\overline{C}_0 = 1$; 2 – $\overline{C}_0 = 2$; 3 – $\overline{C}_0 = 3$; 4 – $\overline{C}_0 = 4$; 5 – $\overline{C}_0 = 5$.

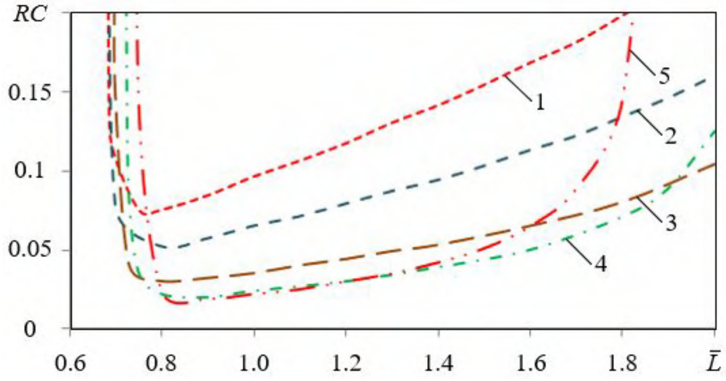

Figure 3. Dependence of reduced costs on packed bed height $\left(\overline{C}_0 = 1\right)$: $1 - \bar{t}_f = 100$; $2 - \bar{t}_f = 200$; $3 - \bar{t}_f = 300$; $4 - \bar{t}_f = 600$; $5 - \bar{t}_f = 900$.

character indicates the existence of extremely low values of L_{min}, at which the filter is able to operate only during the first run for a given value t_f.

Similar analysis for irregular algorithm and arbitrary composition of iron contamination is supposed to be carried out at the next stage of our research. In the near future, it is planned to generalize the available materials on the reaction of the filtration characteristics and economic indicators on the second key design parameter – the size of filter medium elements (effective grain diameter).

5. Conclusions

Based on the results of technical and economic analysis of physical and chemical iron removal at different bed layer heights and levels of iron contamination of water, effective algorithms for long-term control of the filter are developed and tested. It is possible to minimize the reduced costs and the cost of water treatment due to the practical application of these algorithms.

The high sensitivity of economic indicators and, first of all, of the reduced costs in relation to the main design parameter has been revealed. It is shown on the basis of technological modeling of iron hydroxide removal during the service life of the rapid filter medium it is realistic to achieve a significant reduction in the cost of water treatment due to a reasonable choice of the bed layer height taking into account the initial water contamination.

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The influence of the war on the content of some components in the rivers of Ukraine

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The influence of the war on the content of some components in the rivers of Ukraine

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Abstract. As a result of hostilities, the surface waters of Ukraine may be polluted by various components. This can significantly affect the safety of drinking water supply and the ability of water bodies to self-clean. The article is devoted to the calculation of modified water pollution indices and the assessment of water pollution for some Ukrainian rivers that may have been affected by the war. We calculated the modified water pollution index and assessed water pollution for 7 points of 5 Ukrainian rivers (Desna, Dnipro, Styr, Siversky Donets and Oskil) that may have been affected by the war. The modified water pollution index also included nitrates and polyphosphates, unlike the conventional water pollution index. River conditions were assessed from 2018 to 2023 in order to compare water quality in these rivers before and after active hostilities began in February 2022. The most significant effect of military operations on water quality in 2022 was seen at the Siversky Donets and Oskil rivers in the Kharkiv and Donetsk regions, where there were numerous ongoing hostilities. Pollution by biogenic components did not exceed the self-cleaning capacity of these rivers, but bioremediation methods can be used to accelerate the return to normal conditions. Despite being in a conflict zone in the spring of 2022, this had minimal impact on the water quality of the Desna and Dnipro rivers near Kyiv in the summer of 2022. The water quality of the Styr river was improved due to absence of active military actions near the river and significant decrease in tourism and agricultural use of territories.

1. Introduction

During hostilities, the safety of using tap water depends not only on possible cases of sabotage on drinking water treatment plants or plants and pipes destruction due to explosions, but also on unpredictable changes in the quality of natural waters [1]. Military actions can cause damage to the environment in many ways. As a result, natural water, soil and air can be significantly polluted. Pollution of rivers and farmland is of particular concern, as it can lead to poor quality drinking water and food. In most Ukrainian cities, treated water from rivers is used as tap water. Thus, the pollution of rivers can significantly affect the health of the population, if the water cannot be purified to the standard quality [2]. Currently, in warfare, water weaponization has a place to achieve strategic or tactical advantages. Water weaponization is the use of water as physical arms to harm and gain leverage over an adversary by limiting access to water, degrading water quality and creating a shortage of safe drinking water [3].

The ways of military actions influence on water quality in rivers can be divided into direct and indirect (figure 1). Direct ways of influence can include drowning of military vehicles equipment and shells and also decomposition of dead organisms. Rivers are frequently targeted for the deployment of explosives, such as aerial bombing or minelaying, either due to their proximity to settlements, their importance as transportation routes, or the strategic significance of associated structures, such as bridges, irrigation canals, jetties, hydroelectric dams, etc. [4]. Heavy metals can leach from military vehicles, weapons and ammunition. According to analysis of bottom sediments from the lake in Bucha district (Kyiv region, Ukraine) [5], iron content increased from 360.5 mg/kg in 2022 to 1722.0 mg/kg in 2023, manganese level rose from 10.5 to 50.0 mg/kg, copper and aluminium contents grew up from 0.9 and 237.0 mg/kg to 2.0 and 691.0 mg/kg, respectively. A significant increase in the concentrations of heavy metals was also observed in the Molochna River (Zaporizhia region, Ukraine) as a result of hostilities [6]. Significant excesses were observed for Cu, Pb, Cr and Ni (950, 20.7, 4.8 and 10.6 times higher than the maximum permissible concentrations). In addition, the drowning of vehicles can lead to the pollution of water bodies with various petroleum products, which are part of fuel and grease, as well as products of thermal decomposition and incomplete combustion. Drowning ammunition can lead to the leaching of explosives from them, which are often highly toxic. As a result of the decomposition of dead organisms, water is not only polluted with decomposition products, but also the level of dissolved oxygen decreases in water, which can lead to the death of aquatic organisms.

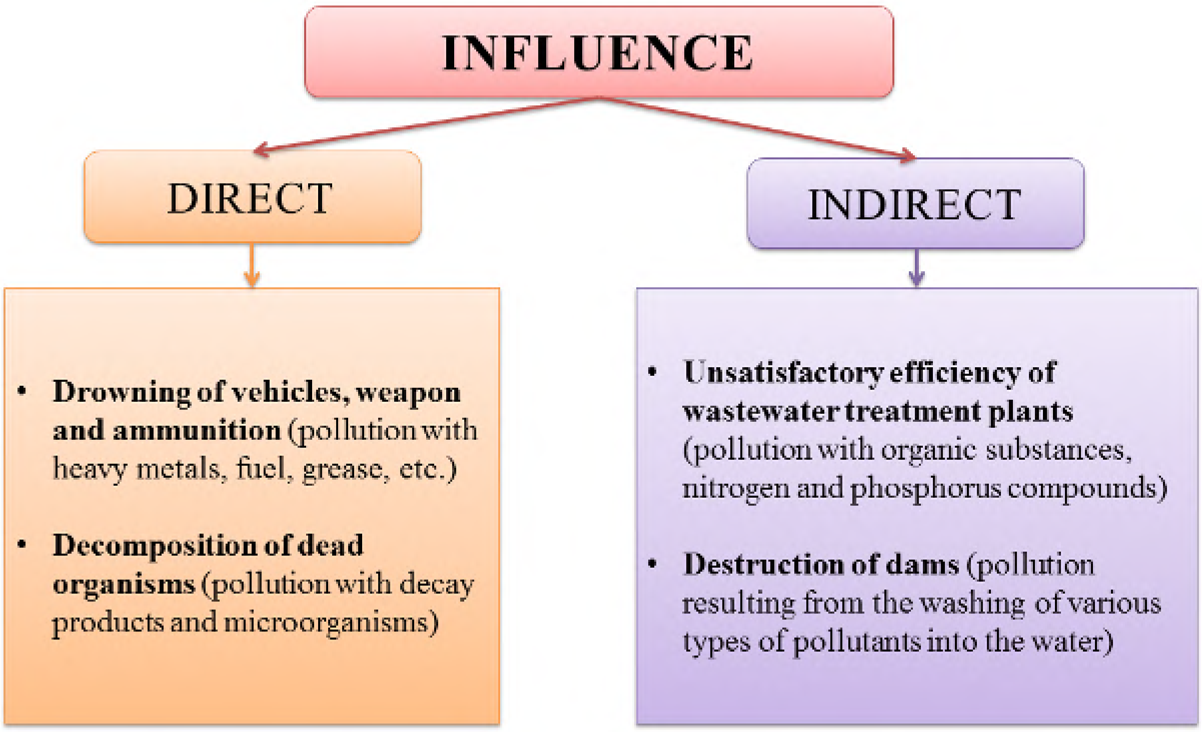

Figure 1. Military actions influence on water quality in rivers.

In addition to direct effects, water quality in rivers can deteriorate as a result of various cases that arise as a result of war. Destruction of dams causes washing of various types of pollutants into the water especially due to flooding of landfills. Wastewater treatment plants can function inefficiently due to blackouts, shortage of reagents for wastewater treatment, partial damage of the plant. As a result, significant amounts of nitrogen compounds, including ammonium nitrogen, nitrites and nitrates, as well as organic matter and phosphorus compounds, including polyphosphates, can enter the river.

Currently, the impact of the war on the state of the rivers of Ukraine is not yet sufficiently studied, since most of the pollution cases occurred in 2022 and 2023. In addition, the main part of research concerns pollution with heavy metals, while pollution with biogenic elements is almost not investigated. Although, unlike heavy metals, biogenic elements cannot lead to extremely long-term pollution of the ecosystem, but such pollution can lead to substantial disturbances in the ecosystem and significant deterioration of water quality due to unbalanced eutrophication.

Identifying rivers whose water quality has deteriorated as a result of direct or indirect effects of war is critical for timely remediation and remediation method selection, as different methods, including biological [7] and chemical [8, 9] approaches, are used for different pollutants.

2. Methods

Water quality monitoring data were obtained from the State Agency of Water Resources of Ukraine [10]. 7 points on 5 rivers of Ukraine, which could be polluted as a result of military operations, were selected for assessment:

1) Desna river, 3 km, drinking water intake in Kyiv (Dnipro river basin, data from Basin water monitoring laboratory);
2) Styr river, 48 km, village Zarichne near the border with Belarus (Dnipro river basin, data from Laboratory of water and soil monitoring in the Rivne region);
3) Dnipro river, 897 km, Vyshhorod, lower beif of the Kyiv hydroelectric station, drinking water intake (Dnipro river basin, data from Basin water monitoring laboratory);
4) Siversky Donets river, 522 km, Raigorod Dam in Slovyansk, drinking water intake into the Siverskyi Donets-Donbas canal (Don river basin, data from Basin water monitoring laboratory);
5) Siversky Donets river, 527 km, drinking water intake of the utility company "Company Water of Donbass" (Don river basin, data from Basin water monitoring laboratory);
6) Siversky Donets river, 540 km, Slovyansk drinking water intake (Don river basin, data from Basin water monitoring laboratory);
7) Oskil river, 112 km, downstream Kupyansk (Don river basin, data from Water and soil monitoring laboratory).

River conditions were assessed from 2018 to 2023 in order to compare water quality in these rivers before and after active hostilities began in February 2022. Water pollution index is usable method to evaluate of water quality of natural water, especially in the cases of using water bodies for drinking water production or fishering [11, 12]:

$$WPI = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{C_i}{MPC_i},$$

where C was concentration of the component in river water, mg/L; MPC was maximum permissible concentration of the component in river water, mg/L.

To assess the quality of river waters, we used a modified water pollution index, which, unlike the conventional water pollution index [12], also included nitrates and polyphosphates, which allowed for a more accurate assessment of pollution by biogenic components.

Formula for calculation of a modified water pollution index:

$$WPI_m = \frac{1}{6}\Big(\frac{C(NH_4^+)}{MPC(NH_4^+)} + \frac{C(NO_2^-)}{MPC(NO_2^-)} + \frac{C(NO_3^-)}{MPC(NO_3^-)} + \frac{C(BOD)}{MPC(BOD)} + \frac{MPC(O_2)}{C(O_2)} + \frac{C(PolyPO_4^{3-})}{MPC(PolyPO_4^{3-})}\Big).$$

In this article, the water quality is assessed only point by point, but differential equations [13] can be used for a generalized assessment of the state of the river or its part.

3. Results and discussion

After the start of active hostilities in February 2022, the modified water pollution index increased rapidly for most of the studied points (figure 2). In 2022, among the studied points, the greatest impact of military actions on water quality was in the case of the Siversky Donets and Oskil rivers, the basins of which are located in the Kharkiv and Donetsk regions, where at that time there were many active hostilities.

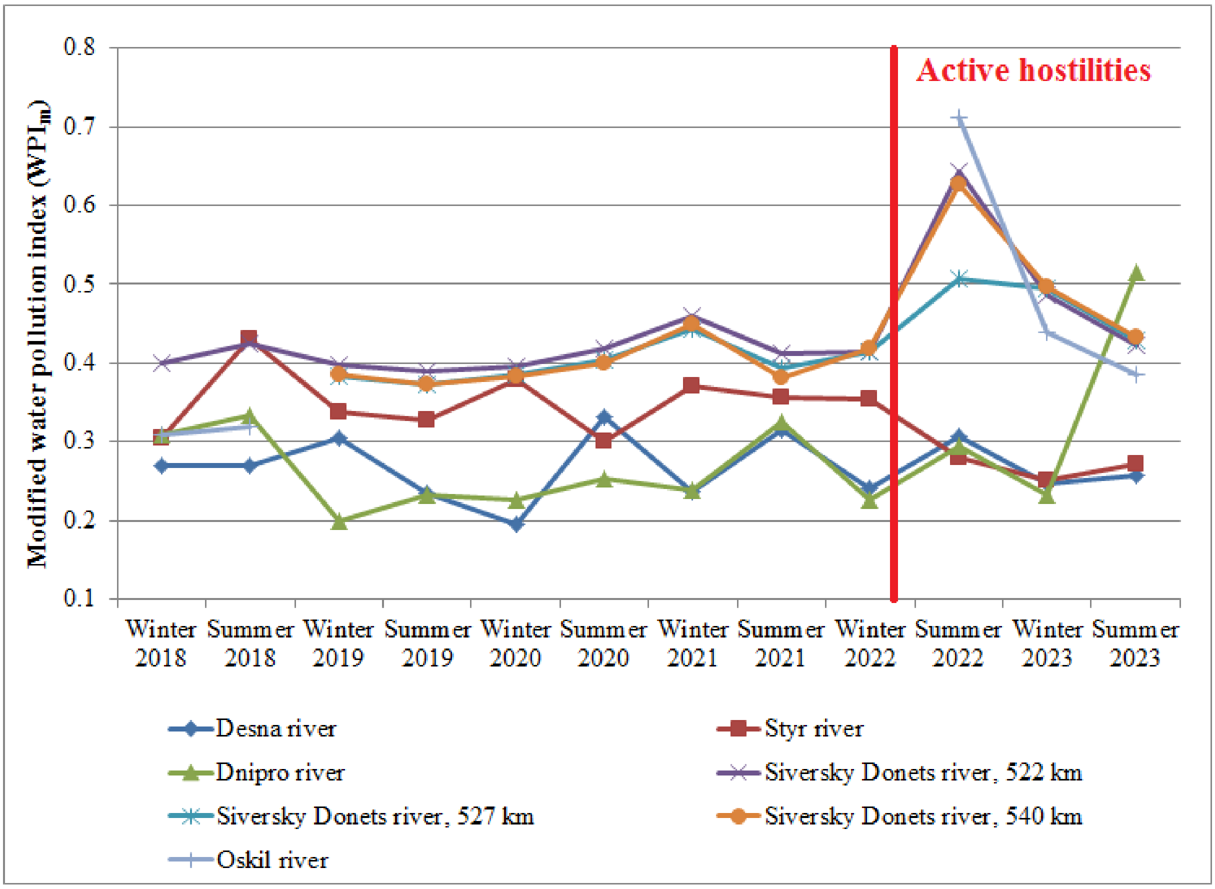

Figure 2. Influence of active hostilities on the modified water pollution index.

Although during the spring of 2022, a significant part of the Kyiv region was a zone of active warfare, this did not significantly affect the quality of water in the Desna and Dnipro rivers near Kyiv in the summer of 2022. In the case of the Dnipro river, significant changes in the modified water pollution index were observed only in the summer of 2023, which may be related to the shelling of the infrastructure. Such a rapid increase could not be caused by seasonal natural phenomena, since in the case of the Desna river located nearby, there was not notable deviations from the reproduced seasonal changes.

In the case of the Styr river, after the start of the active war, the water quality did not deteriorate and even improved. The basin of this river did not belong to the zone of active warfare, and the war led to a significant decrease in the presence of civilians near the border with the Republic of Belarus, and therefore to a decrease in anthropogenic water pollution.

Although the modified water pollution index did not change significantly for the Dnipro river after the start of active hostilities, an increase in ammonium levels (in the range of 0.89-1.09 mg/L) was observed from the summer of 2022 to the summer of 2023 (figure 3). This could be caused by the inefficient operation of wastewater treatment plants and the decomposition of organic matter.

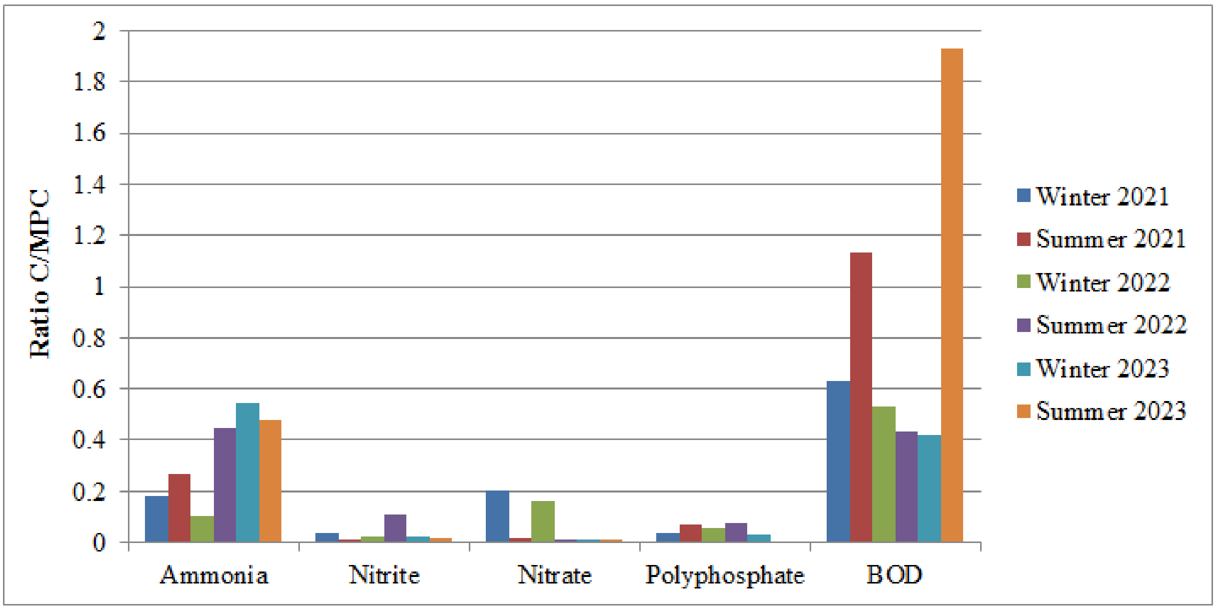

Figure 3. Influence of active hostilities on the water quality of the Dnipro river near Vyshhorod.

A sharp increase in the modified water pollution index in the summer of 2023 is caused by a strong increase in BOD (figure 3), i.e. the content of easily degradable organic substances. The rise and suspension of bottom sediments as a result of shelling could be the reason of such growth.

In the summer of 2022, a significant increase in the concentrations of ammonium (1.63 mg/L), nitrites (0.49 mg/L), polyphosphates (3.01 mg/L) and easily degradable organic substances (BOD 3.86 mg O2/L) were observed in the water of the Siversky Donets river (figure 4).

As a result of active hostilities in the Kharkiv and Donetsk regions, the agricultural use of these areas at that time practically did not take place, so such rise in levels could not be due to leaching of fertilizers from the soils. Thus, the inefficient operation of wastewater treatment plants and the decomposition of organic matter were also the most likely reasons.

4. Conclusions

The pollution of rivers and farmland is a major concern due to its potential to result in low-quality drinking water and food. Heavy metals, petroleum products, microorganisms, products of incomplete combustion, as well as biogenic components can be pollutants of water. Unlike

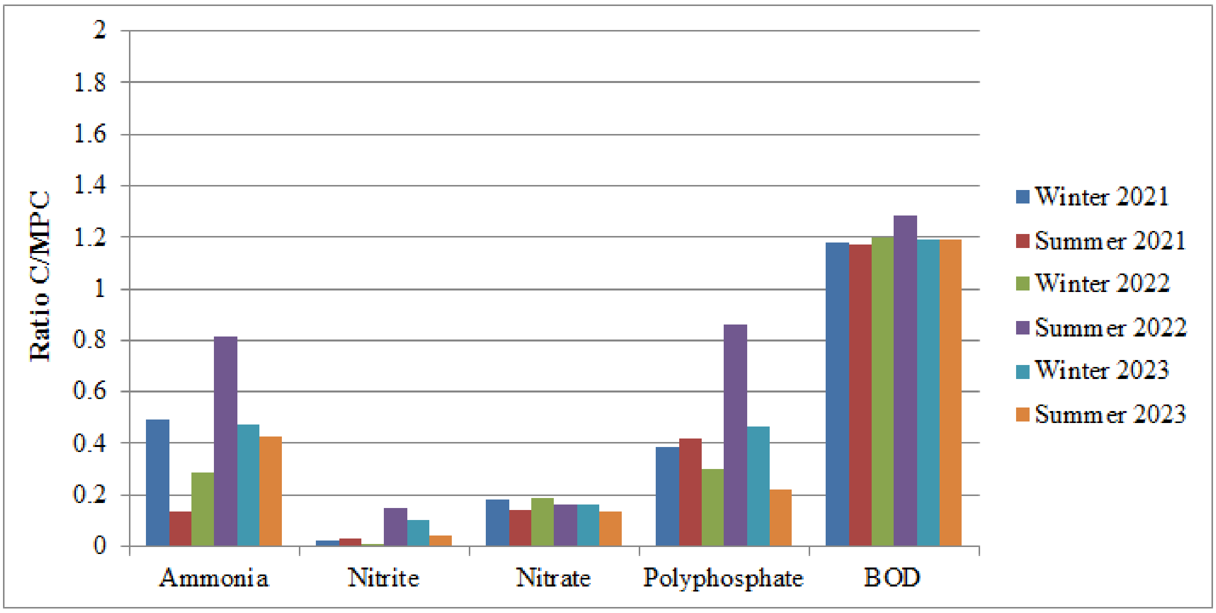

Figure 4. Influence of active hostilities on the water quality of the Siversky Donets river near Slovyansk.

heavy metals, biogenic elements may not cause long-term pollution of the ecosystem, but they can still lead to significant disruptions and deteriorate water quality due to unbalanced eutrophication.

We calculated the modified water pollution index and assessed water pollution for 7 points of 5 Ukrainian rivers (Desna, Dnipro, Styr, Siversky Donets and Oskil) that may have been affected by the war. The modified water pollution index also included nitrates and polyphosphates, unlike the conventional water pollution index. It is suitable for a more accurate assessment of pollution by biogenic components. River conditions were assessed from 2018 to 2023 in order to compare water quality in these rivers before and after active warfare began in February 2022.

The onset of active hostilities in February 2022 resulted in a rapid increase in the modified water pollution index at most of the surveyed points. The largest impact of military actions on water quality in 2022 was observed at the Siversky Donets and Oskil rivers, located in the Kharkiv and Donetsk regions, where there were numerous active hostilities. The inefficient operation of wastewater treatment plants and the decomposition of organic matter were the most likely reasons of such pollution. These plants may operate ineffectively as a result of power outages, a lack of reagents for wastewater treatment, or partial damage to the facility.

Despite being a zone of active hostilities during the spring of 2022, this had a little impact on the water quality of the Desna and Dnipro rivers near Kyiv in the summer of 2022. Following the outbreak of active warfare, the water quality of the Styr river did not worsen and in fact, improved. This was due to the fact that the river basin was not within the active conflict zone, and the war resulted in a significant reduction of civilian presence near the border with the Republic of Belarus, leading to a decrease in anthropogenic water pollution.

Pollution by biogenic components did not exceed the self-cleaning capacity of the considered rivers, but bioremediation methods can be used to accelerate the return to normal conditions. These pollutants can be easily consumed by plants in the process of bioremediation.

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Investigation of the groundwater level dynamics in the rice system under different parameters of irrigation and drainage network

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Investigation of the groundwater level dynamics in the rice system under different parameters of irrigation and drainage network

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Abstract. The dynamics of groundwater level formation on two types of rice irrigation plot were studied: "rice irrigation plot with an irrigator-discharge in a notch and with drainage channels CCD" and "rice irrigation plot with an irrigation channel in an embankment and with drainage-discharge channels (KTC)" with various design parameters of the drainage network. On the basis of long-term field observations of the groundwater level (GWL) lowering on the CCD and KTC with use a network of observation wells, differences in the intensity and uniformity of drying of these types of rice irrigation plots in the pre-harvest and inter-vegetation periods have been established. It has been established that a more favourable water-air regime takes place in the rice irrigation plots CCD with different parameters of the drainage network compared to the rice irrigation plots KTC. At CCD, due to the draining effect of the irrigator-discharge, the field dries out more intensively after the water discharge process. This allows the rice harvest to be carried out in an optimal and rather short time. The presence of the irrigator-discharge as the element of the CCD allows to supply and divert water in a short period of time, evenly over the entire area as well as to perform the role of shallow drain and contribute to intensive drying and desalination of soils. It has been established that the yield of rice on CCD higher than on KTC with the corresponding parameters (on average 400–500 kg$\cdot$ha^{-1}). It has been established that due to these advantages, the rice yield on the CCC the inter-drainage distance 200 m and 250 m is on average 5–7 centner$\cdot$ha^{-1} higher than on the KTC with the same parameters, and higher than on the CCD with the inter-drainage distance 500 m on 17 centner$\cdot$ha^{-1}.

1. Introduction

The modern rice irrigation system (RIS) is a complex set of water supply, drainage, regulating and other elements interconnected by a single technological process in combination with rice fields, on which the leading crop of flooded rice and accompanying agricultural crops are grown.

The main element of any engineering rice irrigation system is the rice irrigation plot. How successfully the design of the rice irrigation plot was chosen and its parameters were selected depends on how successfully it will perform its functions, which are creating an optimal salt, water and air regimes for flooded rice and accompanying crops in the rice irrigation plot. The creation of a favorable salt, water and air regimes determines the conditions for the formation of the ecological and amelioration states on the lands of the RIS and, accordingly, the yield of both flooded rice and accompanying agricultural crops [1–7].

In addition, the productivity of agricultural machinery during the performance of various agrotechnical operations, the productivity of irrigators, and the rational use of irrigation water depend on the design features of the rice irrigation plot and its main parameters.

The composition and construction of the rice systems of the Danube region during their construction were determined by various factors, in particular, climate conditions [8], the fact that they are all located in territories with complex hydrogeological and soil-forming conditions, characterized by the close occurrence of mainly highly mineralized low-flow groundwater [1, 3, 4, 9–11]. This in itself presupposed the presence of a powerful drainage network in the construction of rice systems, which also combined the functions of a discharge system and was called a drainage-discharge network.

Drainage on the RIS is the main means of maintaining a favorable ecological and amelioration state, without which it is impossible to obtain high yields of flooded rice and accompanying agricultural crops.

One of the main tasks of drainage is to ensure the necessary level regime of groundwater in different periods of vegetation, especially in the pre-harvest and inter-vegetation periods of both flooded rice and accompanying agricultural crops [3, 4].

One of the main issues that have been studied throughout the existence of the RIS is the determination of the optimal inter-drainage distances and depth of the drainage-discharge network [9–11]. They must ensure the following functions: compliance with the optimal terms and norms of rice field drainage before harvesting and in the inter-vegetation period; ensuring optimal depths of groundwater level during growing of accompanying agricultural crops; maintaining uniform desalinization of soils both in terms of area and depth; preventing secondary salinization of soils. According to these authors, the optimal inter-drainage distances in the case of saline soils with heavy granulometric composition, both in terms of land reclamation and economic points are within 150–200 m. For soils with a light granulometric composition, depending on the degree of their salinity, depth and mineralization of groundwater, it is recommended to take the value of inter-drainage distances within fairly wide limits – from 200 to 500 m.

As for the design features of rice irrigation plots of the RIS, only certain ameliorative aspects of their operation and efficiency have been sufficiently studied [12–15]. Today, there are practically no results of research on the peculiarities of the formation of groundwater regimes in rice fields with different design parameters.

2. Materials and methods

The aim of research is to study the dynamics of groundwater level formation on the lands of the RIS depending on the design features of rice irrigation plots, as well as the influence of intensity and direction of filtration processes on the ecological and amelioration states on the lands of the RIS and the yield of the leading crop of flooded rice. Therefore, the article aim is comparison of effectiveness of two types of rice irrigation plots design, evaluation their influence on the formation of the water and salt regimes and yield of the leading crop of flooded rice.

The research was carried out during 2011–2016 on three experimental rice fields with various parameters and designs on the Danube RIS located in the Odessa region (Danube Delta) within the framework of a comprehensive program to improve the overall efficiency of the operation of the rice systems in the Danube Delta (figure 1).

The first experimental rice field consisted of two rise irrigation plots, which we call for better understanding “rice irrigation plot with an irrigator-discharge in a notch and with drainage channels (CCD)”. In this type of irrigated areas, the irrigator-discharge performs the role of irrigation channel (supplies water to the rice field) and discharge channel (removes water from the rice field). The average depth of such channel was only 0.7–1.0 m. The inter-drainage distance distance which drain filtration water from the rice field, amounted 200 m. As a control

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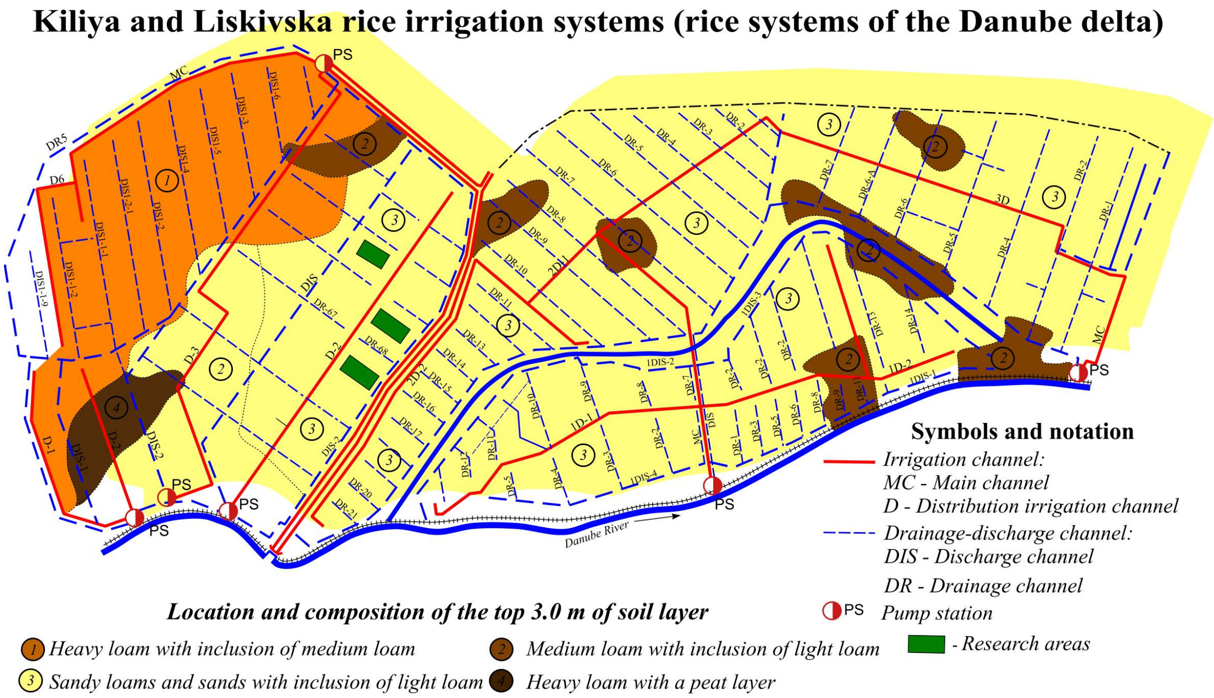

Figure 1. The map of rice systems under research.

plot was chosen the rise irrigation plot of Krasnodar type, which we call "rice irrigation plot with an irrigation channel in the embankment and with drainage-discharge channels (KTC)". In this case, the irrigation channel was used to supply water to the rice field, and the drainage-discharge channels were used to remove filtration and discharge water. The distance between drainage-discharge channels was also 200 m.

The second experimental rice field also consisted of two rice irrigation plots (CCD) and the control irrigation plot of Krasnodar type (KTC), but the inter-drainage distance on the CCD and the drainage-discharge channels on the KTC of both rice irrigation plots was 250 m.

The third experimental rice field consisted of two rice irrigation plots CCD with the inter-drainage distance 250 m for the first plot and 500 m for the second plot.

Schemes of two types of rice irrigation plot – CCD and KTC are presented in figure 2.

The study of the dynamics of the groundwater level was carried out using a network of boreholes that formed longitudinal and transverse cross-sections. On each of the experimental plots, three transverse and one longitudinal borehole-lines with five boreholes in each were arranged. With the inter-drainage distance 200 m, the boreholes in the transverse borehole-lines were placed on both the KTC and the CCD with the distance of 15 m, 25 m, 50 m, 75 m and 90 m from the drain (figure 3), on the CCD at 250 m – at the distances of 15 m, 30 m, 60 m, 90 m and 115 m, and at 500 m – at the distances of 15 m, 60 m, 125 m, 190 m and 240 m (figure 4).

On the basis of long-term observational data processing, it was possible to get an idea of the intensity of the lowering of the groundwater level on the area of rice fields with different design parameters both after the final discharge of water from them and about the dynamics of the groundwater level in rice fields during the inter-vegetation period and during cultivation of flooded rice and accompanying agricultural crops.

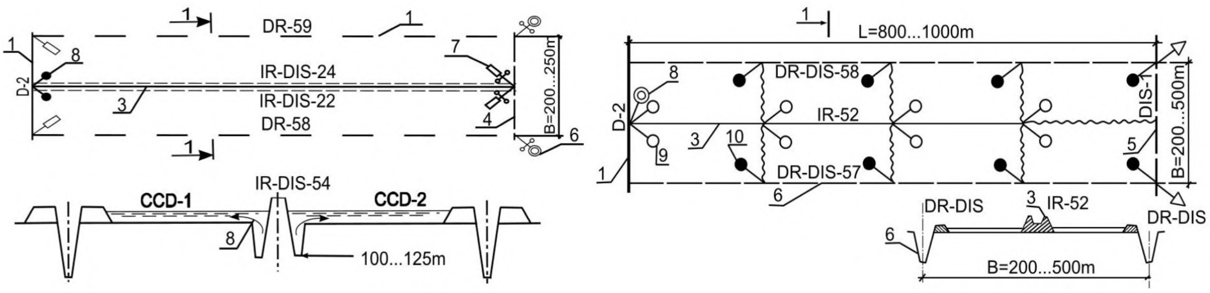

Figure 2. Schemes of two types of rice irrigation plot (CCD and KTC) on the Danube rice irrigation systems: 1 – distribution irrigation channel (D2); 2 – discharge channel (DIS-1); 3 – drainage channel on CCD (DR-58; DR-59), or drainage-discharge channel on KTC (DR-DIS-57; DR-DIS-58); 4 – irrigator-discharge of unilateral command (IR-DIS-22; IR-DIS-24; IR-DIS-54); 5 – water outlet from the distribution channel to the irrigator-discharge; 6 – water outlet from the irrigator-discharge to the discharge channel; 7 – water outlet from the drainage channel to the discharge channel; 8 – water outlet from the distribution channel to the irrigation channel in the embankment; 9 – irrigation channel in the embankment (IR-52); 10 – water outlet from the field to the drainage-discharge channel; 11 – water outlet from the irrigation channel to the field.

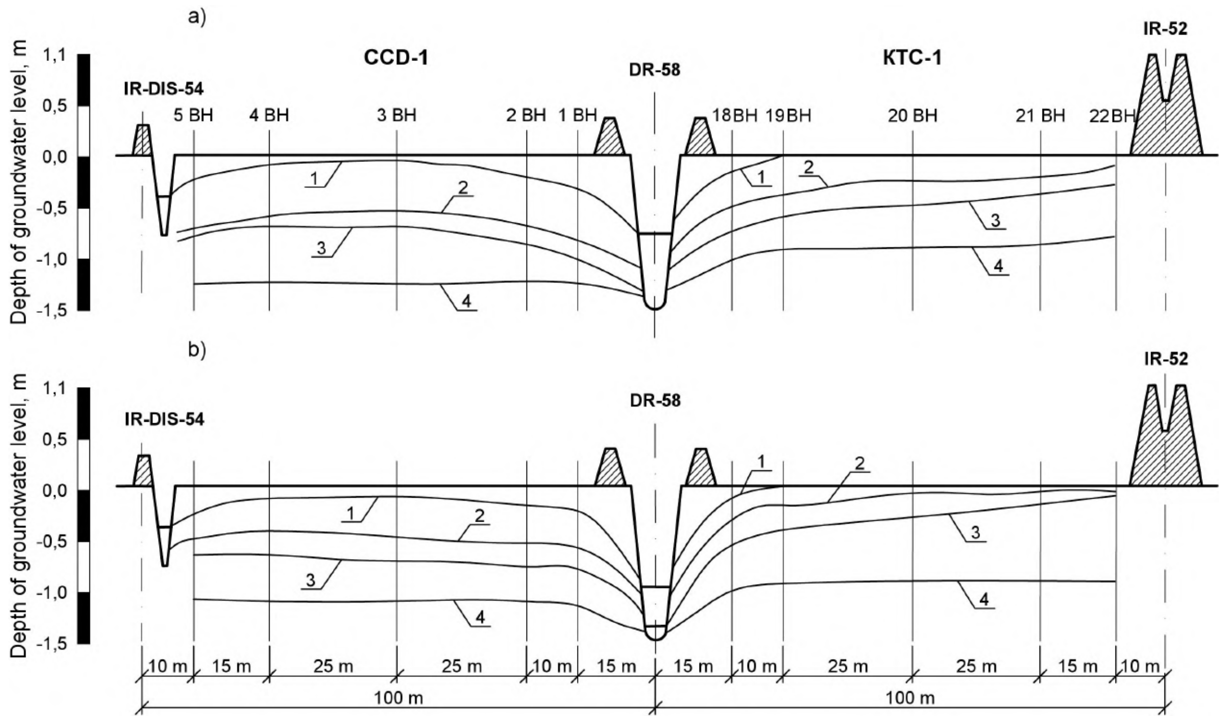

Figure 3. The dynamics of the groundwater level lowering on CCD and KTC after discharging water from rice fields for the 4th (a) and 5th (b) years of the rice irrigation plot No. 1 (inter-drainage distance of 200 m): 1 – after 1 day; 2 – after 5 days; 3 – after 10 days; 4 – after 30 days; 1 BH, 2 BH – 22 BH – observation boreholes.

3. Results and discussion

The duration of the pre-harvest drying of rice fields is one of the most important indicators of the operation of the rice system and its drainage, especially in conditions of saline soils. The terms

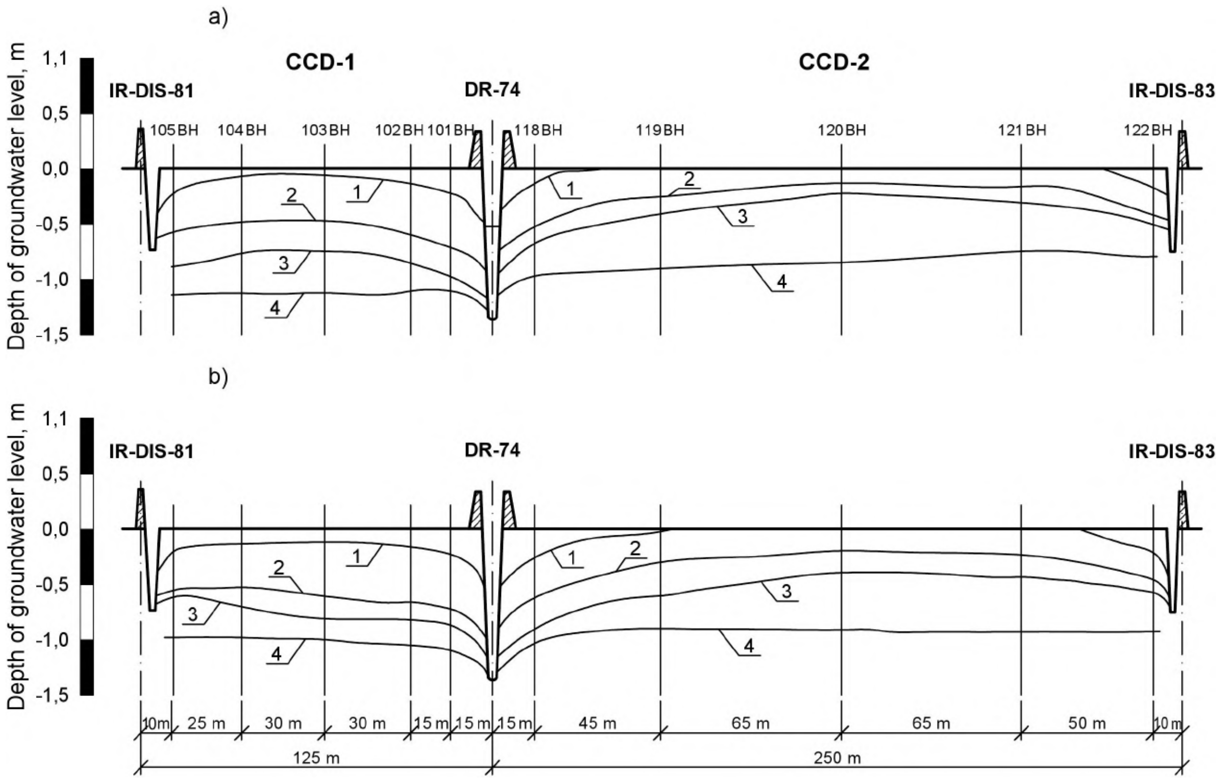

Figure 4. The dynamics of the groundwater level lowering on CCD after discharging water from rice fields for the 4th (a) and 5th (b) years of the rice irrigation plot No. 3 (inter-drainage distances of 200 m and 500 m): 1 – after 1 day; 2 – after 5 days; 3 – after 10 days; 4 – after 30 days.

of harvesting and carrying out autumn field work depend on the duration of the pre-harvest drying [9].

The inability of the drainage network to maintain the necessary rate of drainage and, accordingly, sufficient aeration of the root-containing soil layer in the inter-irrigation period and the related intensity and directionality of oxidation-reduction processes in the soil, as well as to ensure their washing under the influence of filtration flows, are the main reasons for the occurrence of unfavorable soil processes on the RIS (formation of gravelly soils, secondary salinization and waterlogging, etc.), reducing soil fertility and, accordingly, the yield of rice and related crops.

The results of the groundwater level observations on CCD and KTC by using the network of boreholes indicated the existence of differences in the intensity and uniformity of the drying process in these types of rice irrigation plots.

As can be seen from figure 3 and figure 4, on CCD in the first 10 days of drying, the depression curve has a well-defined slope in two directions – to the open drain and to the irrigator-discharge, which indicates the operation of the irrigator-discharge during this period as a shallow drain. Precisely due to the draining effect of the irrigator-discharge the process of the groundwater level lowering in the rice field during the pre-harvest drying occurs much faster on the CCD than on the KTC.

Evaluating the intensity of the pre-harvest drying on the area of the rice fields, it can be noted that in the first 10 days after the discharge of water from the fields, in the conditions of CCD the intensity is the highest within the lanes adjacent to the open drain and to the irrigator-discharge, and the lowest – in the central part of the field (figure 3 and figure 4). On the KTC the groundwater level also decreases, with the highest intensity – in the lanes along the open drain, and the lowest intensity – in the lanes along the irrigation channel in the embankment (figure 4).

The intensity of the groundwater level lowering on the area of rice fields, regardless of the type of construction, for all studied inter-drainage distance (200, 250 and 500 m) is the highest within the zones adjacent to both the discharge channel, the open drain and the irrigator-discharge, and the lowest – in the central part of the fields (figures 5-7).

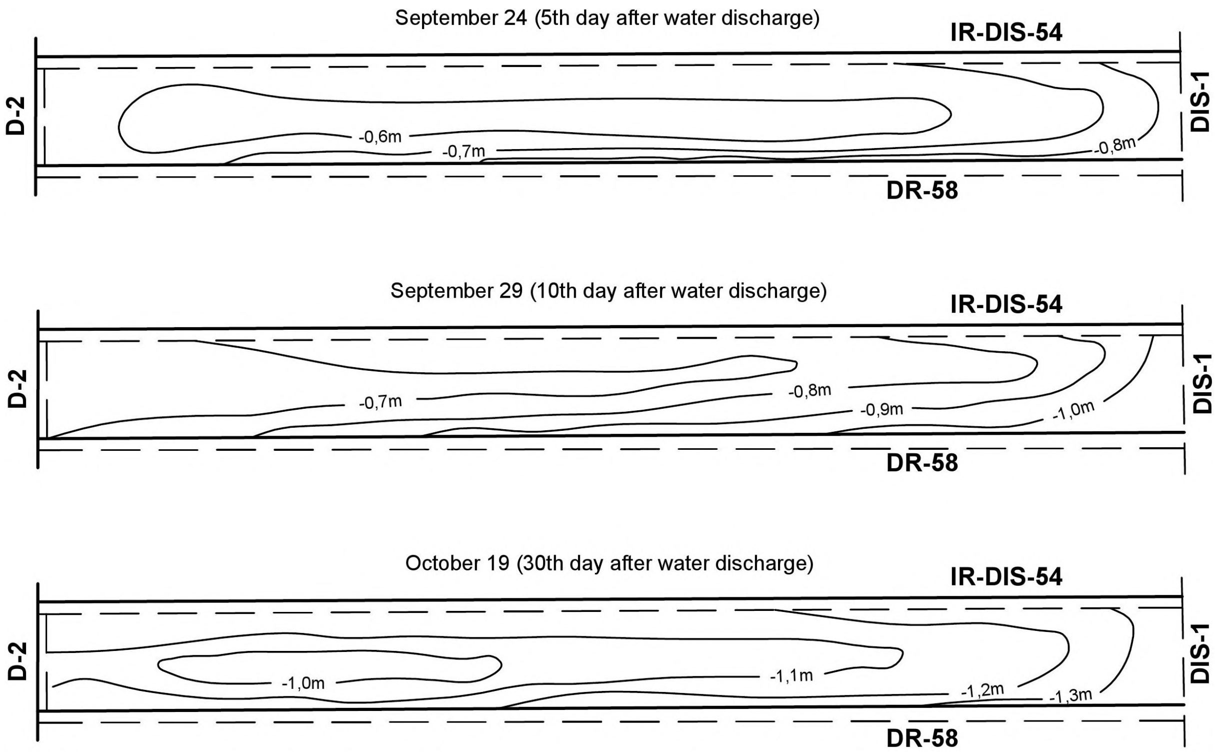

Figure 5. Drying of CCD of the rice irrigation plot No. 1 (inter-drainage distance of 200 m).

In the central part of the fields with the inter-drainage distance 200 m during the first five days after the discharge of water, the depth of lowering the groundwater level (GWL) is about 60 cm, and with 500 m it is only 20 cm (figures 5-7). A similar situation observes on the 10th day after the discharge of water, for example, with the inter-drainage distance 200 m and 250 m the GWL decreases by 70–80 cm, then with the inter-drainage distance 500 m – only by 40–50 cm.

Therefore, the most difficult conditions for the operation of grain-harvesting equipment and other agricultural machines during the harvest period will arise precisely in the central part of the rice fields. Precisely for this zone of rice fields, according to the data from measurements of the position of groundwater in the central boreholes, correlations between the depth of groundwater level in the experimental rice irrigation plots and the duration of their drainage were established. These correlations are expressed by the following regression equations:

a) for CCD with inter-drainage distance of 200 m

$$H = 8.15 + 65.49 \cdot LgT, \tag{1}$$

b) for CCD with inter-drainage distance of 250 m

$$H = 2.24 + 69.36 \cdot LgT, \tag{2}$$

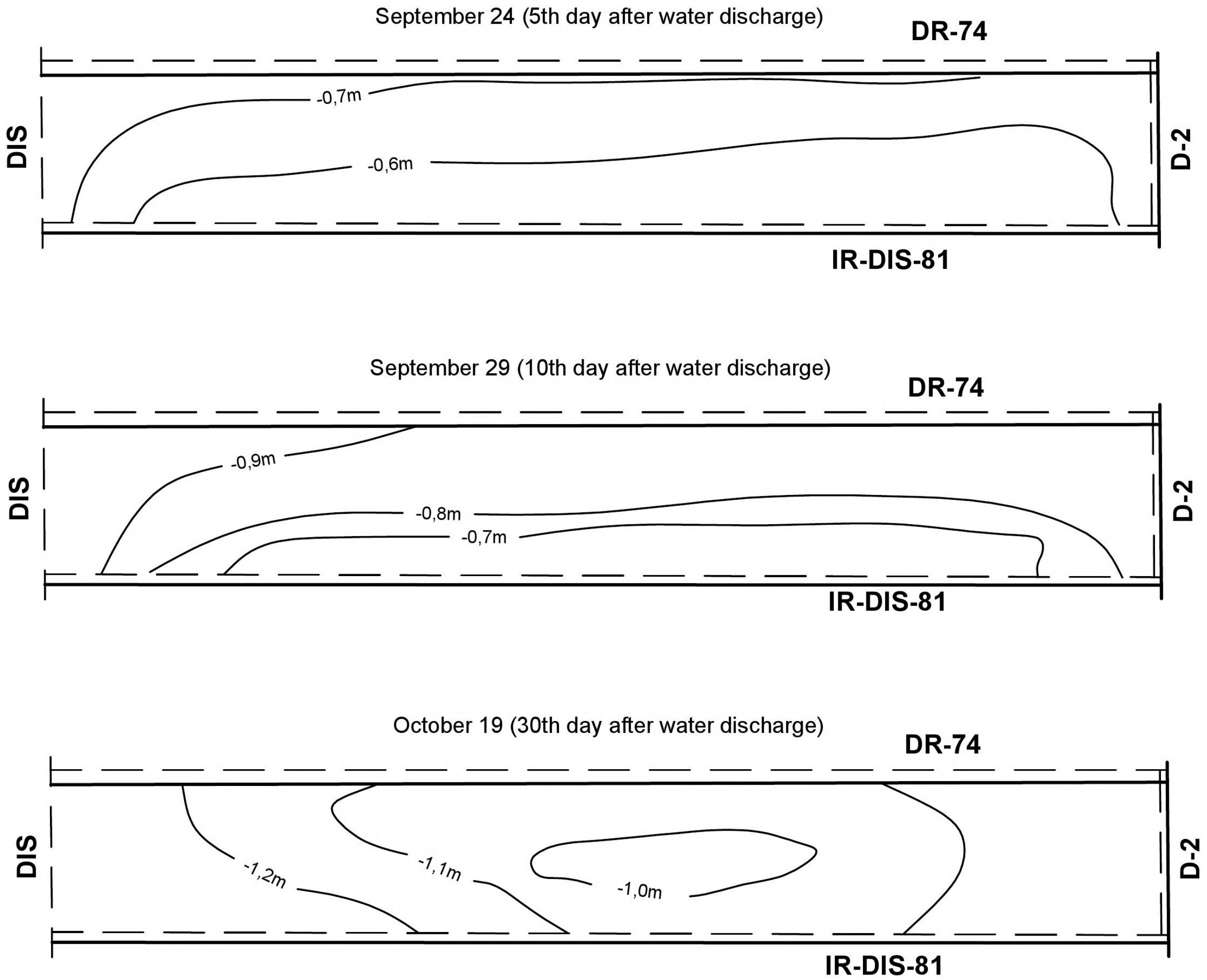

Figure 6. Drying of CCD of the rice irrigation plot No. 3 (inter-drainage distance of 250 m).

c) for CCD with inter-drainage distance of 500 m

$$H = 2.78 \cdot T - 1.13, \tag{3}$$

d) for KTC with inter-drainage distance of 200 m

$$H = 3.07 \cdot T + 3.82, \tag{4}$$

e) for CCD with inter-drainage distance of 250 m

$$H = 3.06 \cdot T + 0.28, \tag{5}$$

where H – the depth of the groundwater level from the field surface at a certain moment in time, cm; T – duration of field drying, days.

For regression equations (1) and (2), the correlation coefficients are 0.95 and 0.91, respectively, and for regression equations (3), (4) and (5), the correlation coefficients are 0.98, 0.99 and 0.97 respectively. Such high values of the correlation coefficients testify to a close relationship between the correlated values and show that climatic factors do not have a determining influence on the intensity of the groundwater level lowering in the rice fields. The intensity of the groundwater level lowering is mainly determined by the design features of the drainage and discharge network.

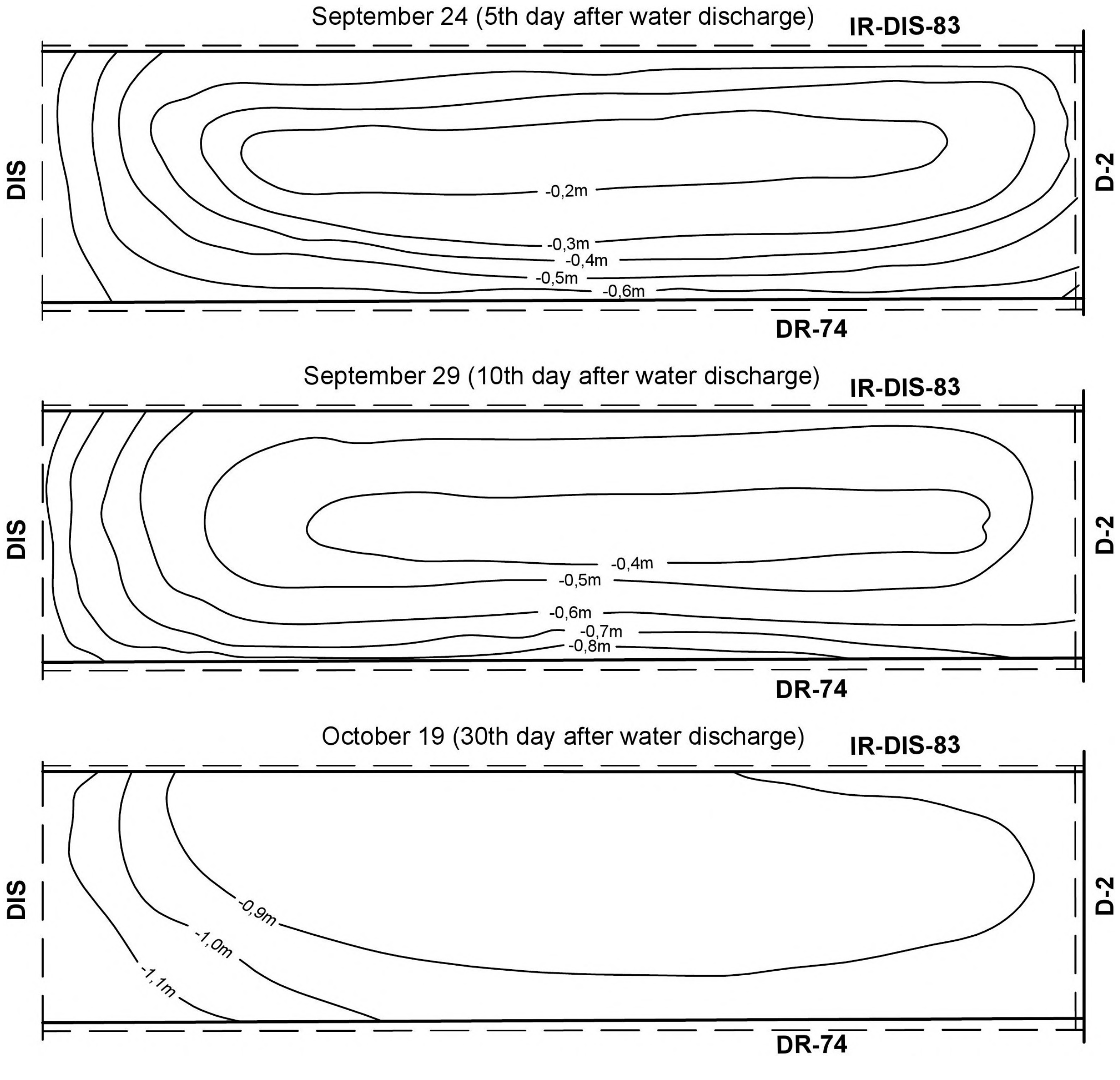

Figure 7. Drying of CCD of the rice irrigation plot No. 3 (inter-drainage distance of 500 m).

The graphs of the groundwater level lowering during the pre-harvest drying on the area of the rice fields, which were obtained according to regression equations (1–5), are shown in figure 8. They can be used to forecast the duration of the pre-harvest drying on the area of the rice fields with different parameters of the drainage network for the Danube RIS. With their help, it is possible to establish the terms of the groundwater level lowering in the rice fields to the depths under which a highly productive and high-quality harvesting of the rice crop will be possible

For the rice systems of the Danube delta, these depths are 0.6 m or more [2,9]. For conditions of CCD with inter-drainage distances of 200 and 250 m, the groundwater level lowering to the required depths is 6–7 days after discharge of water from them (figure 8). It takes 18–20 days for conditions of KTC with the same inter-drainage distances and 22–23 days for conditions of CCD with inter-drainage distance of 500 m. At the same time, the intensity of the groundwater lowering at a distance of 25 m from the drainage channel in the first day after water discharge is 0.2–0.12 m/day, and in the 20th day after water discharge, it decreases to 0.03–0.02 m/day.

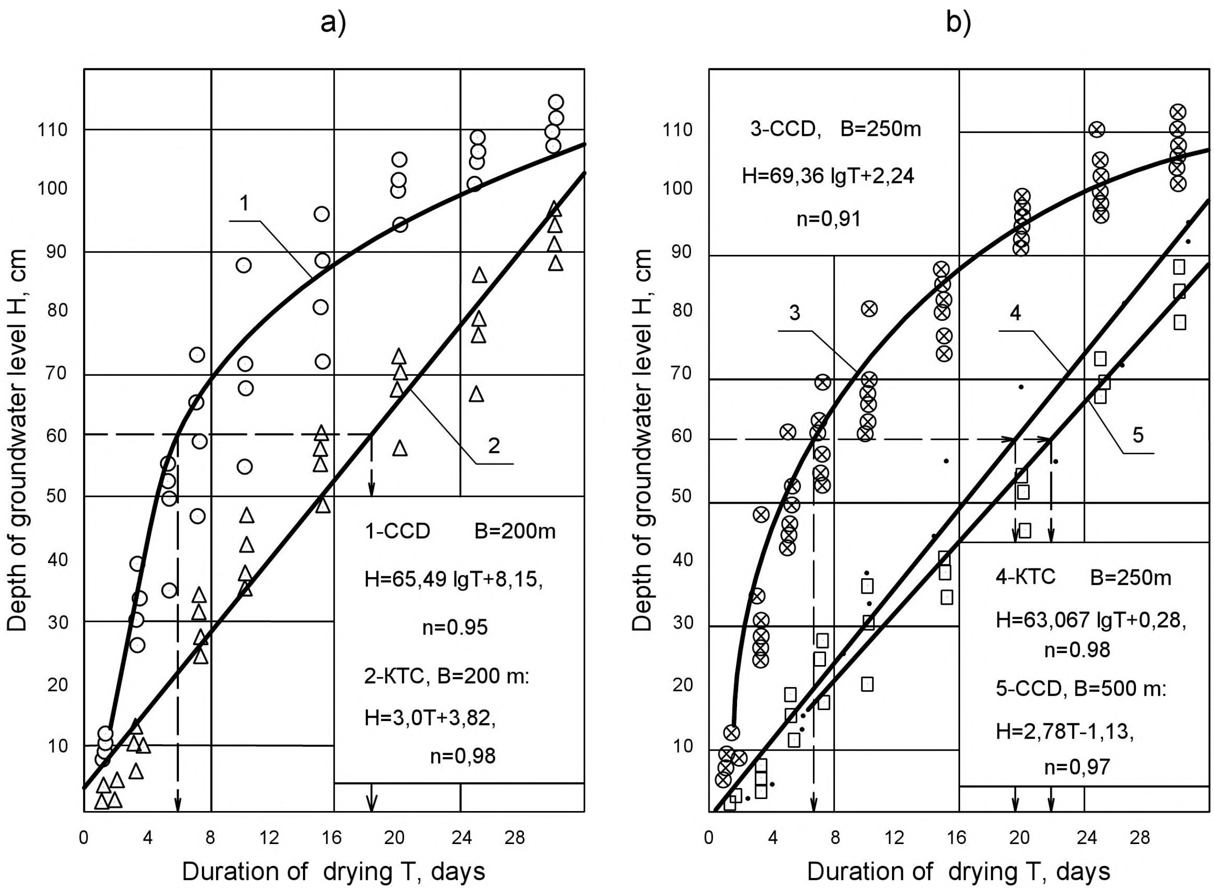

Figure 8. Intensity of the groundwater level lowering in conditions of KTC and CCD with inter-drainage distances of 200 m (a), 250 m and 500 m (b).

At a distance of 100 m from the drainage channel, the intensity of the groundwater lowering is 0.04–0.03 m/day in the first day after discharge and 0.005–0.01 m/day in the 20th day after water discharge (figure 9).

Due to the fact that rice fields of the CCD type with inter-drainage distances of 200 and 250 m dry three times faster than fields of the KTC type with the same parameters, as well as rice fields of the CCD type with inter-drainage distance of 500 m. Accordingly, the harvesting of the rice crop can be started earlier and done in a fairly short period of time. At the same time, harvesting equipment will be used more rationally, and crop losses associated with grain shedding will be minimized, which will positively affect the amount of the gross harvest.

Not only the timing of harvesting depends on the duration of pre-harvest drying but also the timing of autumn field work, namely, tillage (autumn plowing). Autumn plowing has a number of advantages over spring plowing, especially if it is carried out in September or at the beginning of October, since later times of its implementation reduce the yield of the crop [3, 4]. For conditions in the rice systems of the Danube Delta, autumn plowing of soils can be carried out when the groundwater level in the rice fields is reduced to a depth of at least 0.8 m. It takes 12–14 days to reduce the groundwater level to such depths on fields of the CCD type with inter-drainage distances of 200 and 250 m, 25–27 days for fields of the KTC type with the same parameters, and about 30 days for fields of the CCD type with inter-drainage distance of 500 m (figure 8).

Since the discharge of water from rice fields in the Danube RIS is carried out mainly in the

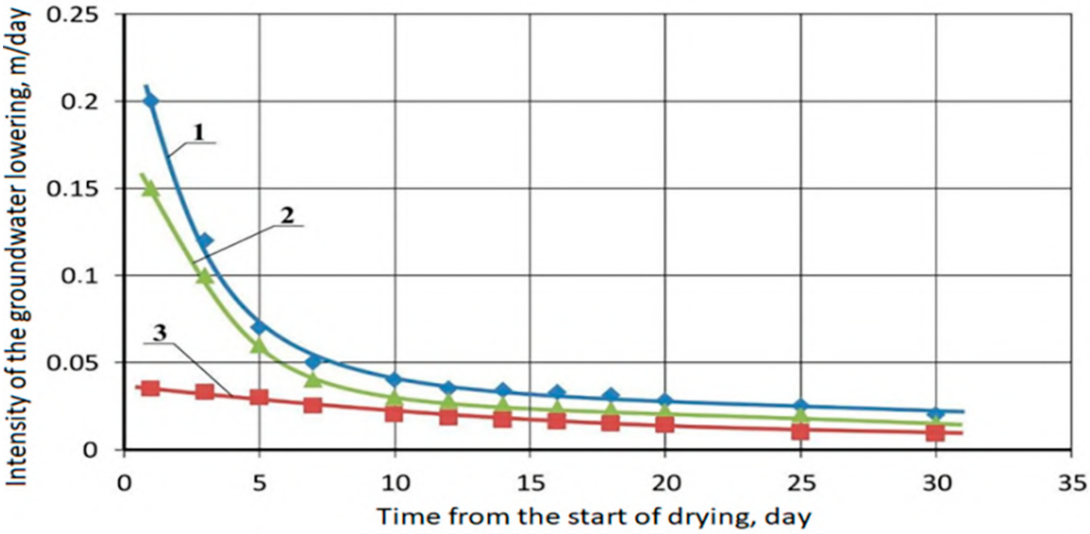

Figure 9. The graph of the groundwater lowering intensity change after water discharge from the rice fields for conditions of CCD with inter-drainage distance of 200 m (1 – at a distance of 25 m from the drainage channel, 2 – at a distance of 50 m from the drainage channel, and 3 – at a distance of 100 m from the drainage channel).

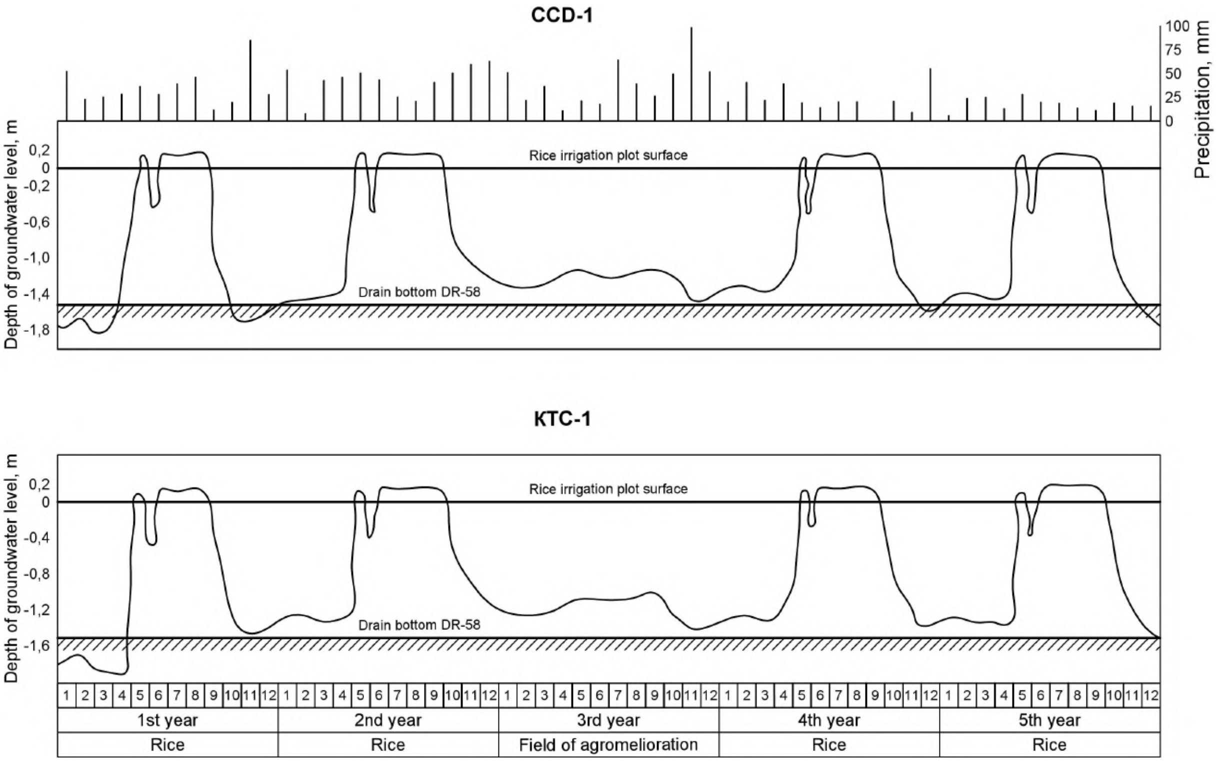

Figure 10. Change of groundwater level position in the rice irrigation plot No. 1 (for CCD and KTC with inter-drainage distance of 200 m).

second half of September, taking into account the terms of drying of the fields, it is possible to carry out autumn plowing at the optimal time only on the CCD type with a gap of up to

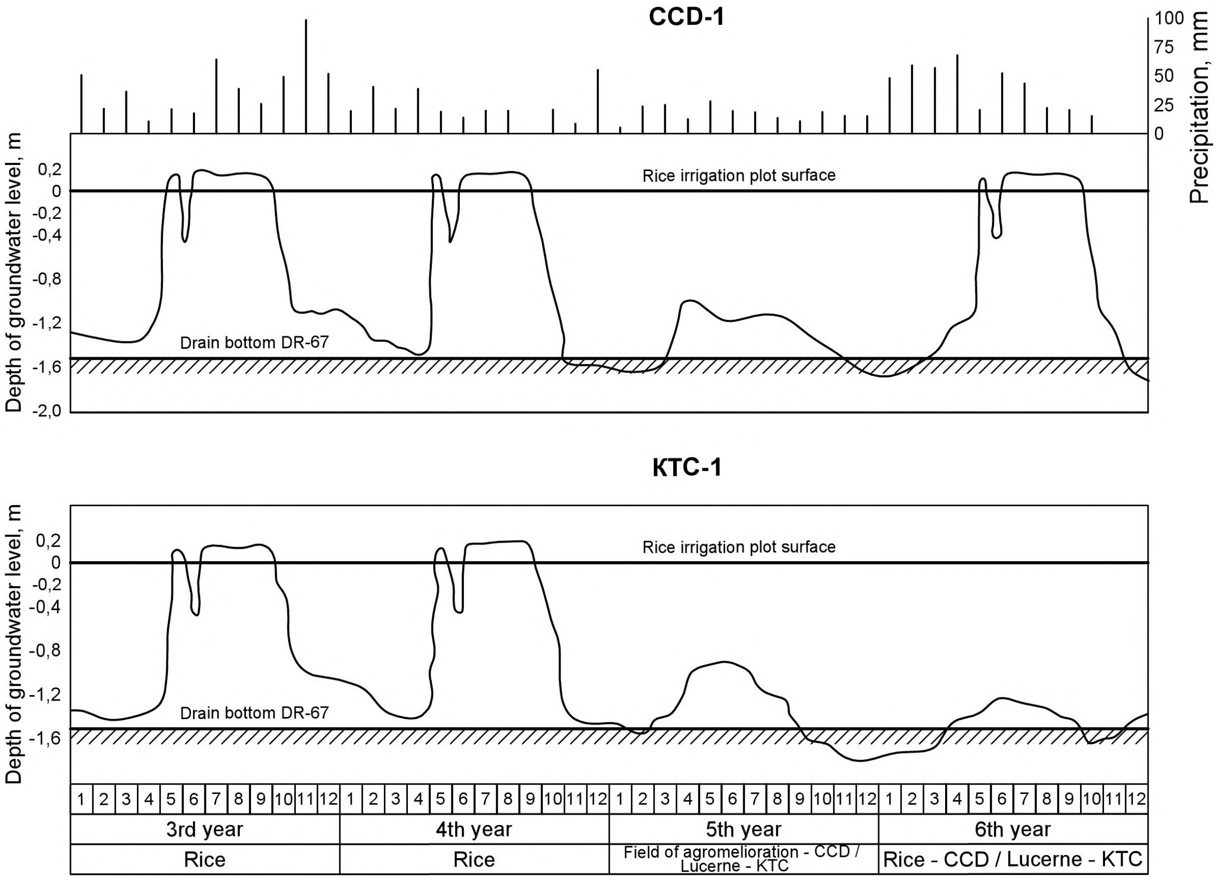

Figure 11. Change of groundwater level position in the rice irrigation plot No. 2 (for CCD and KTC with inter-drainage distance of 250 m).

250 m. It is almost impossible to carry out this measure in the optimal time on fields of the KTC type with inter-drainage distances of 200 and 250 m and on fields of the CCD type with inter-drainage distance of 500 m. In some cases, due to the large amount of precipitation that fell in November, it becomes impossible to carry out autumn plowing at all, as we observed in some fields of the KTC type.

An important indicator of the effective operation of the drainage and discharge network in rice fields is the maintenance of groundwater level within optimal during the inter-vegetation period. In [12] it was established for the conditions of researchers in other areas of rice sowing that obtaining high rice yields is possible when the groundwater level occurs during the inter-irrigation period at depths of more than 1.5–2.0 m [14–17]. With such depths of groundwater level in rice fields, aeration conditions are improved and salinization of the root layer of soils is prevented.

In the areas with a close occurrence of the groundwater level (0.5–0.6 m), reduction processes are intensified in the upper horizon, which leads to the accumulation of divalent forms of iron (Fe^{2+}), hydrogen sulfide, mobile manganese, and ammonia nitrogen, the pH value increases, and the content of nitrate nitrogen decreases. At the time of sowing rice, the soil does not have time to oxidize well, which causes poor crop germination and, as a result, a drop in the rice crop harvest.

Since the highest level of groundwater is typical for the central parts of rice fields, graphs of changes in the groundwater level were constructed for boreholes located in the center of

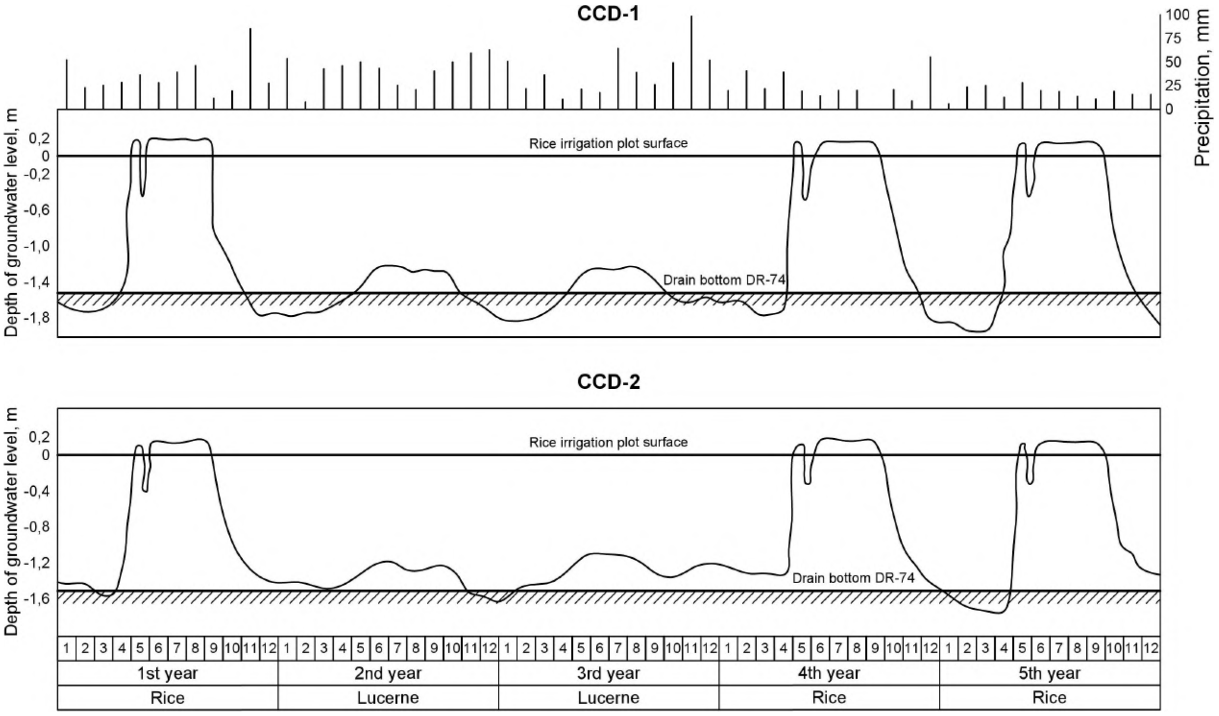

Figure 12. Change of groundwater level position in the rice irrigation plot No. 3 (for CCD with inter-drainage distance of 250 m and for KTC with inter-drainage distance of 500 m).

experimental plots CCD and KTC (figures 10–12).

According to the received data, it was determined that after 30–60 days after the discharge of water from the fields of the CCD and KTC types with inter-drainage distances of 200 and 250 m, approximately the same level of groundwater remains, which, before the beginning of the next irrigation season, changes within, close to 1.5 m from the surface of the rice fields. In this case, the level of groundwater practically did not depend on the type of rice irrigation plots but was mainly determined by the depths of the drainage and discharge network and the amount of precipitation in the inter-irrigation period. In some cases, for example, in the autumn of the 1st and 3rd year of the research at the experimental rice irrigation plot No. 1 (CCD), the groundwater level was somewhat lower than at the KTC (figure 10). This is explained by the more intensive drying of fields of this type in the first 15–20 days of pre-harvest drying.

On fields of the CCD type with inter-drainage distances of 500 m, the levels of groundwater during the inter-irrigation period were mainly 0.4–0.6 m higher than in the neighboring fields of the CCD type with inter-drainage distances of 250. Groundwater levels practically did not decrease below a depth of 1.5 m in relation to the surface of the rice fields (figure 11 and figure 12). This was one of the main reasons for the rather low yield of rice on this type of field.

Due to the fact that on the CCD it is possible to create a water regime that best meets the physiological needs of rice culture, as well as due to the uniform and more intensive desalination of filds, a higher rice yield was recorded on them, on average by 5–7 centner·ha^{-1} than on control KTC with the same parameters and by 17 centner·ha^{-1} higher than on the CCD with the distance between drainage channels 500 m.

4. Conclusions

Thus, evaluating the efficiency of operation of the drainage and discharge network of rice fields on the experimental rice irrigation plots in the period of pre-harvest drying and in the inter-vegetation period, the following conclusions can be obtained:

- due to the more intensive and uniform drying of rice fields of the CCD type with inter-drainage distances of 200 and 250 m, they have the most favorable conditions for high-quality and highly productive performance of rice harvesting and autumn field work;
- fields of the KTC type with inter-drainage distances of 200 and 250 m and fields of the CCD type with inter-drainage distances of 500 m dry slowly, as a result, harvesting and tillage are often carried out late. The terms of performance of these works are significantly extended, and in some cases, it becomes impossible to perform autumn plowing of soils;
- during the inter-vegetation period, in all experimental rice irrigation plots, groundwater was observed at depths of 0.2–0.5 m above the optimal limit, and in the fields of the CCD type with inter-drainage distances of 500 m, the groundwater level was almost constantly above the optimal limit;
- in order for the groundwater level to be at the required depth (more than 1.5 m from the field surface) during the inter-irrigation period, regardless of climatic factors, the open drainage and discharge network must have a depth of at least 1.8–2.5 m.

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Geoinformation modeling of the geoecological state of the floodplain-channel complex of rivers on the territory of the Turka city community of the Lviv Region

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Abstract. The Water Strategy of Ukraine for the period up to 2050 [1] identified the main areas for improving water resources management through the creation of automated information systems for eight river basin districts. Conducting geoecological studies using GIS technologies to assess the state of river-basin systems at the level of an individual community in order to optimize water use and water protection is an urgent scientific task. The creation of geographic information models and the formation of the database took place in the environment of software packages: Google Earth Pro, SAGA, QGIS 3.28 Firenze and ArcGIS 10.8. To assess the geoecological state of the floodplain-channel complex of rivers within the territory of the Turka territorial community (TC), the methodology of Khimko et al. [2,3] was chosen, which is modified in accordance with the purpose of the research and specific water bodies. The created geoinformation models of the gynaecological state of the floodplain-channel complex of rivers indicate the need to make effective management decisions to optimize the use of natural resources within the basin and floodplain-channel systems and control over the use and protection of water.

1. Introduction

The Water Strategy of Ukraine for the period up to 2050 [1] outlines the vectors for the development of water management and water resources management, which includes the introduction of eight automated information systems in the relevant areas of river basins by 2032. They will be involved in making management decisions in the field of environmental protection to ensure management, control over the use, protection of water and reproduction of water resources at the national level. At the same time, the administrative reform of 2020 [4] opens up wide opportunities for local communities to dispose of the natural resource (including water resource) potential of the territory of their residence. Therefore, the *urgent* scientific task of today is the analysis of the geoecological state of water bodies at the regional and local levels and the creation of appropriate geoinformation databases that will be used in the development of a water protection strategy for the development of a separate territorial community and the assessment of the investment attractiveness of the territory. The *object* of the study was the Turka community (with an area of 398.8 km^2) as a newly formed administrative-territorial unit within the Sambir district of the Lviv region (Ukraine). Part of the Main European Watershed, which separates the waters of the Baltic and Black Seas, passes through the territory of the Turka urban community. The second important watershed within the community is the Verkhovyna watershed range, which separates the waters of the Dniester and Danube basins [5]. This is the place of origin (source), formation of the flow of many small rivers. Within the study area there is also the Stryi River, which is classified as medium according to the Water Code of Ukraine, and the upper reaches of the large Dniester River. The analysis of the hydrological regime of water bodies and the quality of river waters has been carried out by many scientists and the results of regional comprehensive geoecological studies have been published in monographs [6–12].

Detailed studies of the geoecological state of the upper part of the Dniester basin were conducted by Pylypovych [12]. The state of the environment of the study area is also analyzed in [10, 11].

Among the world's best practices, it is worth mentioning the study by Grizzetti [6], which indicates that the ecological status of rivers in the European Union is influenced by multiple natural and anthropogenic factors at the local and regional levels. This indicates the need for an integrated approach when implementing measures to improve the ecological quality of rivers. Similar conclusions can be traced in [7, 13–18]. Noteworthy is Xu et al. [9], who has developed a new system for assessing environmental parameters for small rivers in Shanghai, using 17 indicators to assess water quality, ecological system, and ecological landscape.

However, detailed large-scale hydroecological studies at the level of a separate territorial community using modern GIS technologies have not been carried out in order to create an information database of geodata and optimize water resources management and water protection.

The analysis of the water resource potential of the territory of the Turka community was carried out by assessing the geoecological state of the floodplain-channel complex of rivers, carried out using GIS technologies and field research materials.

2. Method

Geoinformation modelling of the geo-environmental state of the community territory involved the following research stages: collection of existing information, its processing; conducting own research (field, geoinformation, laboratory and other methods); generalisation of the collected geo-environmental information and formulation of general conclusions.

In the course of the research, a series of large-scale topographic maps, as well as Google satellite images of 2022, open-source OpenStreetMap data, and land cadastre materials were processed [19]. The following software packages were used to create geoinformation models and create the database: Google Earth Pro, SAGA, QGIS 3.28 Firenze and ArcGIS 10.8 [20].

The algorithm for creating geoinformation models included:

1. Search and selection of cartographic sources and satellite images.
2. Preparation of images and satellite images for processing in the geographic information software environment.
3. Coordinate referencing of geospatial data and selection of a coordinate system.
4. Create feature layers in shapefile formats with a geometric element (point, line, or polygon).
5. Digitization of data and addition of information from state cartographic databases.
6. Filling in attributive data taking into account the types of objects, their quantitative, qualitative and spatio-temporal parameters.

7. Carrying out cartometric, analytical, overlay operations to obtain new analytical data on the state of each of the analyzed components of the environment using optimal visualization and presentation techniques.

A method for assessing the geoecological state of the floodplain-channel complex of rivers (test) was proposed by Khimko [2,3,21,22]. It involves determining the state of the channel and floodplain by visual indicators based on their comparison, inspection and comparison, as well as determining changes based on the results of a survey of old-timers in this area. The assessment is carried out by assigning appropriate points. According to this scheme, a river in good condition should receive the highest marks (points); Accordingly, the river in poor condition is not high. The scheme allows the provision, if necessary, of intermediate estimates. There are 5 gradations of the sum of points (5 quality classes), and 23 parameters are analyzed to determine them. These parameters are grouped into three categories: the first is the assessment of the river; the second is an assessment of the state of the floodplain; the third is information from a survey of the population (changes over a period of 10-40 years) about the depth and nature of the changes that have occurred with the river, in comparison with the state that old-timers recall (the use of comparative characteristics – before/after) [21,22].

After summing up the points, according to this methodology, an act of survey and determination of the general geoecological state of the river is drawn up.

3. Results and discussion

The *Turka community* is a territorial community in the Sambir district of the Lviv region (figure 1).

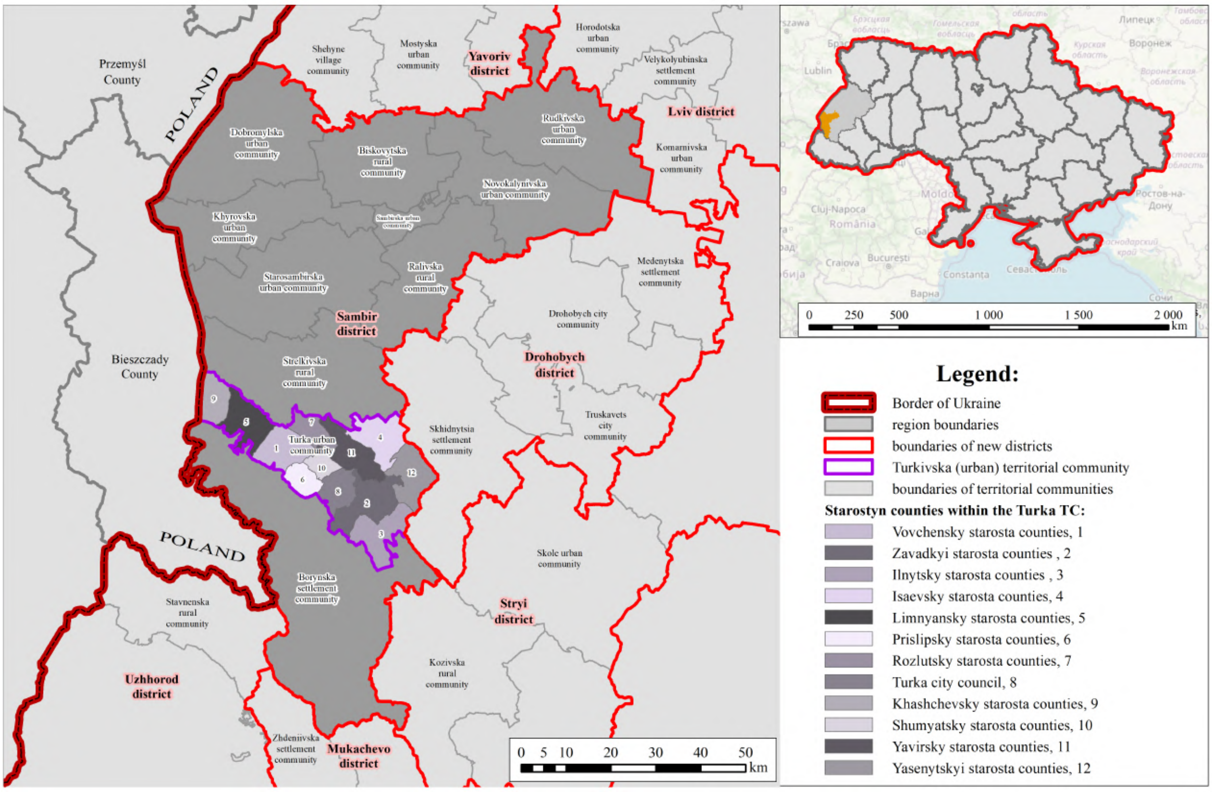

Figure 1. Location of Turka territorial community (complied on the basis of OSM).

Its administrative center is the city of Turka. The area of the community is 398.8 km^2, the population is 23.6 thousand people. people (as of 2022). The population density is 59.17 people/km^2. In the north, the Turka community borders on the Strilky TC of the Sambir district, in the east with the Skhidnytska TC of the Drohobych district, in the south – the Borynska TC of the Sambir district, and in the west – with the Republic of Poland [23, 24].

The hromada consists of 1 city (Turka) and 24 villages, which in turn are united into 11 starosta districts (created on the basis of village councils of the same name).

The total length of watercourses within the territory of Turka TC is 1,282.95 km (obtained from the QGIS statistical report layer). It is worth noting that these are permanent watercourses that do not dry up in summer, but only change the water regime. The river network is formed by: the Dniester River, the Stryi River, the Zavadka River, the Yasenytsia River, the Yablunka River, the Litmyr River, the Kindrativka River, the Zvir River, the Yavirka River, the Yasenychanka River, the Khashchivka River and their tributaries.

The average density of watercourses is 2.21 km/km^2) The data are obtained on the basis of GIS analysis of the river network. This indicator ranges from 0.04 to 6.64 km/km^2) and is characterized as high (figure 2). The highest density of watercourses is concentrated near the village of Vovche – at the headwaters of the Dniester River; in the village of Shumyach, where the Zvir River flows into the Litmyr River; in the village of Ilnyk – near the mouth of the Zavadka River; in the village of Yavora – the confluence of the Yavirka River with the Stryi River; in the catchment area of the Kindrativka River near the villages of Kindrativ and Yasenytsia. Accordingly, the lowest values of the density of watercourses were determined at the community boundary.

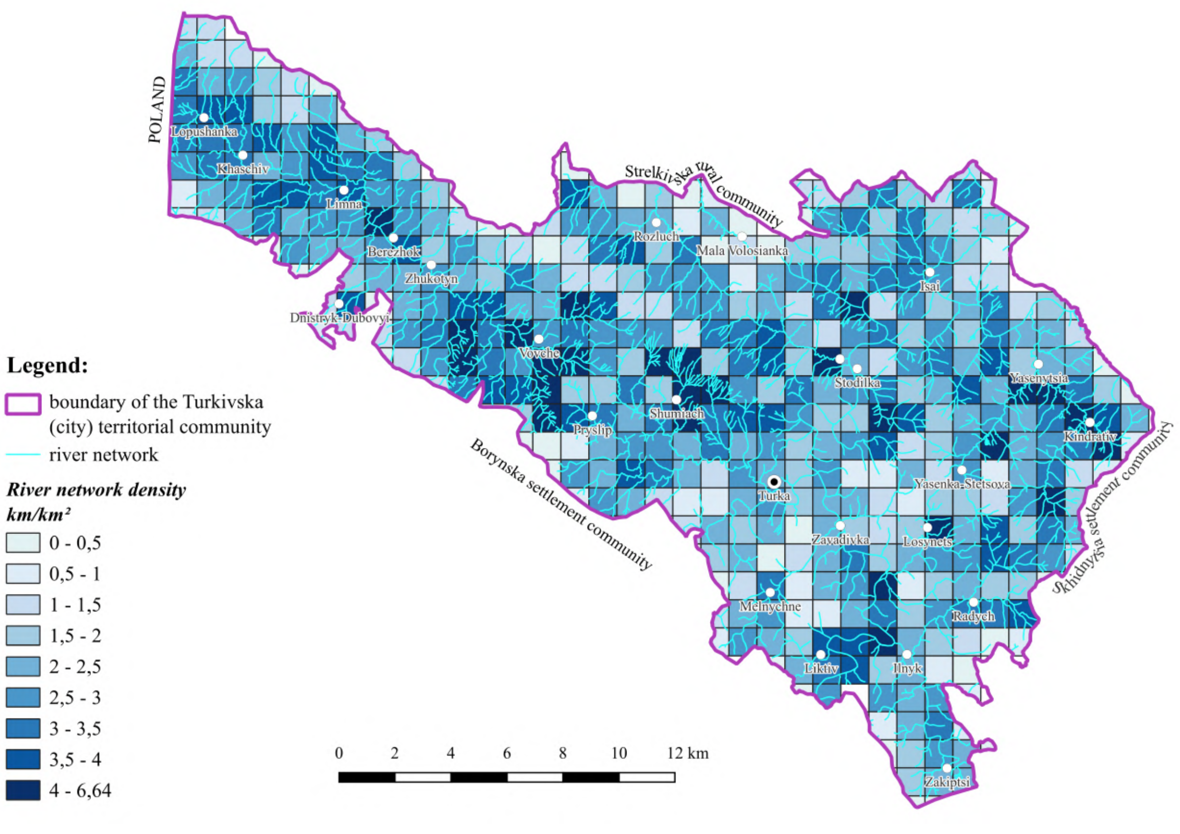

Figure 2. Density of the river network within the study area.

The study of the state of the floodplain-channel complex within the territory of the Turka community was carried out in three standard stages: preparatory, field surveys and office processing of the collected materials by summarizing the results of the assessment of the geo-ecological state of the river according to the test performed.

The preparatory stage consisted in the study of natural conditions and economic factors that affect the formation of the geo-ecological state of the community. Based on these results, it was determined which components of the environment are most affected. It was found that water resources are the most vulnerable within the community, and the impact on other components of the environment is minimal or absent (due to the lack of sources of impact), so our research was further aimed at assessing the state of water bodies [2, 3, 21].

To assess the geoecological state of the floodplain-channel complex of rivers within the territory of the Turka community, the methodology of Khimko et al. was chosen [2, 3, 22], which was modified in accordance with the purpose of the research and adapted to specific water bodies [25]. According to this methodology, a set of parameters (23 indicators in total) was determined, which were interpreted in the form of a point scale, and then, on the basis of their summation, an assessment of the geoecological state of the floodplain-channel complex was given.

At the *preparatory stage*, the following was also developed: routes for field surveys of the state of rivers and their floodplain-channel complexes were developed (on the basis of cartographic studies); key areas of riverbeds and floodplains were selected as priorities for detailed research; evaluation forms (figure 3) and forms of reporting materials are formed; measuring equipment (pre-calibrated and other inventory) has been selected.

Field geoecological studies were carried out according to the plan:

- departure to the study area, inspection of the floodplain-channel complex of rivers when moving along its banks;
- along the main route (at key points) the states of the channel and floodplain were described

Observation point No. 12

Geographical coordinates: 49.112725° N, 23.075748° E

Description of the area

The right bank of the Stryi River, the beginning of Ilnyk village, next to the road. The riverbed is natural - it has all its inherent elements: shallows and deep sections, meandering, with sections with fast and slow flow. The bottom is of a natural rocky type with soft sediment. There are accumulations of objects of unnatural origin. Landscapes within the valley are heavily disturbed, as a large area is used for economic purposes, including buildings. Natural phytocoenoses are heavily modified. Non-compliance with the boundaries of coastal protection zones. There are a significant number of sources of small volumes of runoff. The river and surrounding landscape have changed over the years, but they are still attractive.

Indexes	value
Загальний вміст солей (TDS)	95 mg/dm³
The pH level	7 (l. t. - 7)
Water temperature	13,9 °C
Electrical conductivity (EC)	304 μS/cm
Salinity	0,01 ‰
Specific density (S.G)	1,000 g/l
Redox potential	-42 mV
Flow rate	0,9 - 1,2 m/s
Maximum depth	211 m/s

Identification of organoleptic properties of water		
Indicator	Water colour	Yellowish colour, shade - light yellow.
	Water smell	Subtle, fishy - score 2 points. The comparison was carried out: at collection; 6 hours after collection, where the water was heated to 60 °C; after settling for 24 hours. The smell did not change.
	Transparency	When using the Secchi disc, the water transparency is 40 cm, at a depth of 50-55 cm the transparency is minimal. According to the water column method, the height of the water column is 43 cm.
	Turbidity	The water at this site is classified as slightly opalescent.
	Precipitate	The sediment is noticeable. The quality is of silty-clumpy nature. It is black-brown in colour. During shaking, the precipitate is noticeable.

Methodology (test) for assessing the geo-ecological state of the floodplain and channel complex according to Khimko R.V. et al.

Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	sum
Assessment	10	10	15	8	8	4	6	5	12	8	6	14	3	6	10	7	4	5	6	8	9	10	8	**182**

Figure 3. Survey form of floodplain-channel complex conditions.

and their scores were given in accordance with the described methodology;

- a survey of local residents about changes in the state of the riverbed and floodplain was carried out and estimates in the form of "before/after" were recorded;
- point and diffuse sources of environmental pollution were linked and fixed on the map;
- photographing and mapping of the study area was carried out;
- water quality was assessed by organoleptic indicators;
- search for sites or intermediate points for additional studies was carried out.

The *stage of generalization* of the research results consists in the processing and systematization of the collected information, summing up the results of field work, determining the geoecological state by summing up the scores and their visualization and interpretation in the form of maps.

Based on the results of the test, both general conclusions about the geoecological state of the floodplain-channel complex of rivers and local ones for individual sections (of the same type and representative) were formed.

To assess the geoecological state of the floodplain-channel complex of rivers (GSFCCR), the Stryi and Dniester rivers were surveyed within the territory of the Turka urban community (figure 4).

The following indicators were studied: *I. Assessment of the river:* (flow rate; condition of the riverbed; regulation of the river by dams, ponds or other regulatory structures; nature of the bottom, its siltation; nature of river water; water temperature; clogging of the riverbed; nature of aquatic vegetation; overgrowth of the riverbed; presence of ichthyofauna; state of banks and

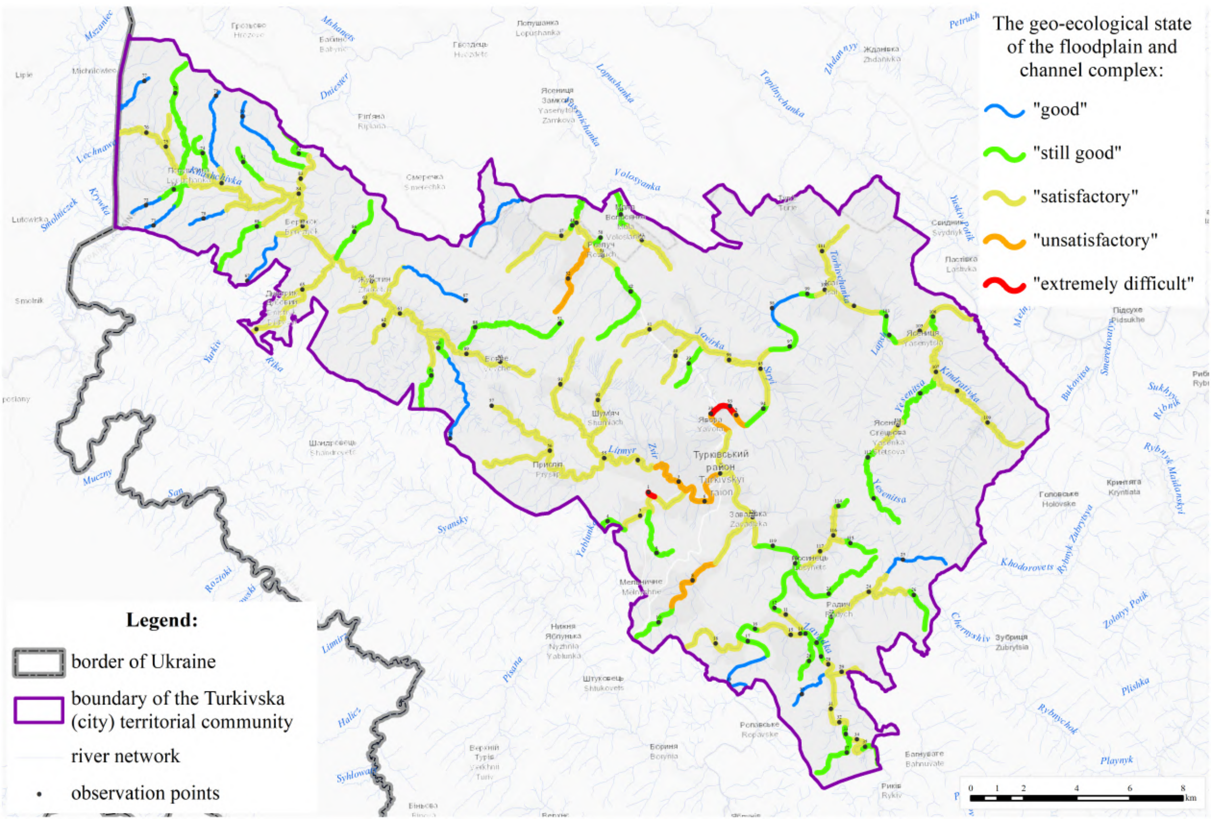

Figure 4. GSFCCR within the territory of the Turka urban community (built for [2, 3, 22]).

coastal protective strip (CPS)); *II. Assessment of the state of the floodplain* (the ratio of natural elements of the floodplain to the transformed ones; the width of the undisturbed part of the floodplain with natural or close to it biocenotic (vegetative) cover, the degree of disturbance of the natural landscapes of the river valley; the degree of degradation of natural phytocenoses of the floodplain; traces of water plane erosion; the level of recreational load; contamination of the coastal protective strip; the nature of the economic use of the floodplain; the presence of residential buildings or other buildings in the floodplain Structures; use of river water, the presence of direct effluents into the river); *III. Information from the population survey* (changes that occurred over a period of 10-40 years).

The total number of key points where we measured the main parameters and mapped the territory is 120 pcs. For their initial display, a Google map was created with free access (for viewing), where the coordinates of these points and other information are indicated [26].

It was found that the general indicator of the geoecological state of the floodplain-channel complex of rivers on the territory of the Turka TC ranges ***from 59 to 253 score***. Of the total:

- 14 points received more than 230 score, where the condition can be assessed as *"good"*;
- 47 points (in the range of 230-170 score), where the condition of the river is *"still good"*;
- 51 points (in the range of 170-120 score), where the condition of the river is *"satisfactory"*;
- 6 points (in the range of 120-65 score) where the condition of the river is *"unsatisfactory"*;
- 2 points (less than 65 score), where the state of the river is *"in extremely serious condition"*.

According to the calculations based on the methodology [2,3,22] the average score is ***172.65 score*** (within the range of 230-170). The general condition of the rivers can be assessed as *"still good"*, but there is a possibility of degradation processes. This should cause concern among local residents and the need to implement a set of preventive measures to preserve and protect rivers; among them, educational and informational activities are particularly important.

As can be seen from (figure 4), the condition of large sections (42.5 percent) of the floodplain-channel complex of rivers (mainly the valleys of the Dniester and Stryi) is assessed as *"satisfactory"*. Negative changes are actively taking place in the river. It is necessary to implement water protection measures for its recovery. It is also expedient to develop and gradually implement a local environmental action plan to reduce the anthropogenic load on multi-rank basin systems within the territorial community.

Sections of watercourses with an indicator of more than 230 score (11.6 percent) were singled out separately, where the state of the river can be assessed as *"good"* and limited only to preventive measures for its preservation, in particular, compliance with the conditions of nature management within the coastal protection zones – restriction of grazing, prevention of regulation of flow and construction of economic structures within the floodplain, as well as clogging of the floodplain and riverbed, etc.

4. Conclusions

The study of the state of the floodplain-channel complex at the level of an individual territorial community using modern GIS technologies and detailed field surveys allows obtaining an information base as a tool for implementing an environmental action plan for the conservation of water bodies at the local level.

Within the territory of the Turka community, only half (50.8 percent) of the studied river-basin systems received an indicator of the state of the river as *"good"* and *"still good"*. These are generally small watercourses – tributaries of the upper Dniester (figure 4). About 7 percent of the sections are characterized by the condition of the river as *"unsatisfactory"* and *"in extremely serious condition"*.

The obtained cartographic materials reflecting the geoecological state of the floodplain-channel complex of rivers on the territory of the Turka community indicate the need to make effective management decisions to optimize nature management within the basin and floodplain-channel systems and control over the use and protection of water.

In particular, ensuring the functioning of the system of coastal protection zones significantly reduces the load on the channel complex due to the prohibition of: plowing land (except for preparing the soil for tinning and afforestation), as well as gardening and horticulture; storage and application of pesticides and fertilizers; arrangement of summer camps for livestock; construction of any structures (except for hydrotechnical, navigational, hydrometric and linear), including recreation centers, summer cottages, garages and parking lots; arrangement of garbage dumps, manure storages, accumulators of liquid and solid production waste, cemeteries, cattle burial grounds, filtration fields, etc.; washing and maintenance of vehicles and equipment.

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Assessment of the distribution and population characteristics of *Musculium lacustre* Müller, 1774 (Mollusca, Bivalvia, Sphaeriidae) in anthropogenically altered aquatic landscapes of the northern right bank of the Dnipro River in Ukraine

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Assessment of the distribution and population characteristics of *Musculium lacustre* Müller, 1774 (Mollusca, Bivalvia, Sphaeriidae) in anthropogenically altered aquatic landscapes of the northern right bank of the Dnipro River in Ukraine

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Abstract. Today, the rapid disappearance of bivalves in European water bodies is a matter of serious concern. The state of study of mollusks of the family Sphaeriidae in Europe, including Ukraine, is considered insufficient, which does not allow to assess their resources, develop measures for protection and restoration of their numbers. The paper assesses the distribution and frequency of occurrence of the small bivalve *Musculium lacustre* Müller, 1774 (Mollusca, Bivalvia, Sphaeriidae) in the anthropogenically altered aquatic landscapes of the northern right bank of the Dnipro River of Ukraine. This species is considered to be quite eutopian, but in the surveyed region it shows a clear tendency to decrease the frequency of occurrence and population density of individuals. The reason for this situation is the disappearance of typical habitats due to the transformation of rivers into a system of ponds and reservoirs as a result of dam construction and pollution. Out of 232 sites analyzed, *M. lacustre* was found in the Pripyat sub-basin in only 5 sites, and in the Teteriv basin (Middle Dnipro sub-basin) in only 2 sites (the frequency of occurrence in these sub-basins is 4% each, and the overall figure for the sampling area is 3%. The maximum population density was 21 in the Hnylopyat River, 11 in the Gusak River, and 1-3 ind./m^2 in other sampling sites, although according to literature data, in the last century it could reach several thousand per m^2 in Ukraine. Found in rivers and streams, it prefers flowing areas.

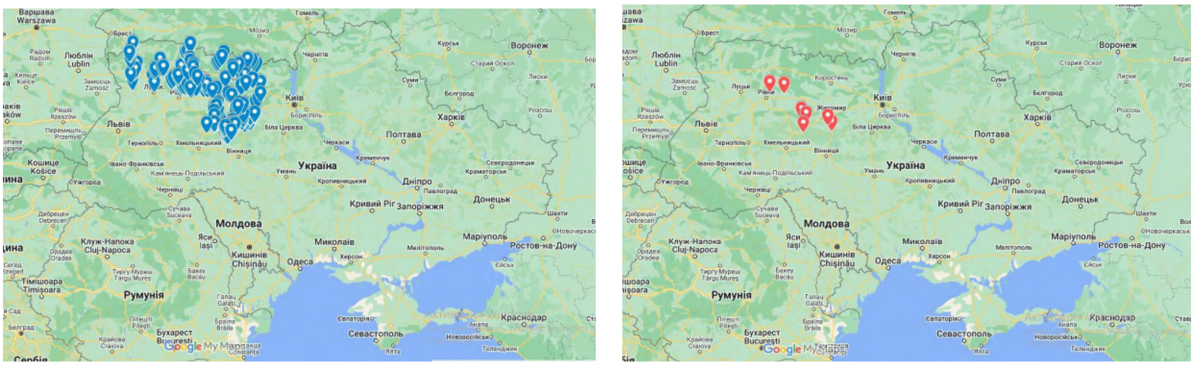
1. Introduction

Freshwater bivalves are important components of hydroecosystems because they provide an important ecosystem service by filtering water and shaping its quality. No freshwater ecosystem can exist without filtering species. Ukraine's integration into the European scientific space, the implementation of the Water Framework Directive [1, 2], and the realization of the Sustainable Development Goals [3, 4] require that information about this group of aquatic organisms in Ukraine be presented on the scientific map of Europe, which will further allow for the planning of joint conservation measures and the inclusion of bivalves in Ukraine in the state water quality monitoring programs for natural water bodies. The issue of water conservation is an acute one in Ukraine. Freshwater bodies, especially rivers, have undergone significant anthropogenic transformation as a result of human activity. Their condition has been affected by damming, land reclamation, discharge of untreated wastewater, unregulated fertilization in areas of intensive agricultural development, pesticide ingress, deforestation, etc. As a result, many groups of aquatic organisms, including bivalves, have seen their numbers in freshwater bodies sharply reduced and often disappear from them due to changes in habitat conditions. The problem of revitalizing rivers, especially small ones, and restoring important and typical groups of aquatic organisms is becoming increasingly acute. Today, 77.3% of freshwater mollusks of the Unionidae family in Europe are already in need of protection and have a protected status, but due to insufficient study, only 8.3% of Sphaeriidae representatives have such a status (Red List). For this purpose, first of all, according to the International Union for Conservation of Nature and Natural Resources (IUCN) Red List criteria (Criterion A and B), it is necessary to estimate the number of their populations and the current area. In total, there are 39 species of mollusks of the family Sphaeriidae in the Western Palaearctic, including two North American invasive species, *Sphaerium transversum* and *Euglesa compressa*, whose invasion aggressiveness has not yet been recorded. The systematics of the group of bivalves Sphaeriidae is one of the most controversial. There is no consensus among malacologists on the number of species that exist in Europe, and in Ukraine, and on the number of genera to which they belong. According to the previously prevailing systematic views, from 21 to 73 species were recorded for the territory of Ukraine at different times. Of the representatives of the genus Musculium, 6 species were recorded for Ukraine. Thus, the only currently recognized species *Musculium lacustre* Müller, 1774, was divided into the following: *M. terverianum* (Dupuy, 1849), *M. hungaricum* (Hazay, 1881), *M. mucronulatum* (Moquin-Tandon, 1855), *M. creplini* (Dunker, 1845), *M. ryckholti* (Normand, 1844), *M. clessini* (Clessin, 1880). Today, according to recent studies [5], all these species are considered to be one species of *M. lacustre* (Marsh Musculium), which belongs to the genus *Musculium*, although French malacologists include it in the genus Sphaerium. The species is distributed in the Palaearctic, in North America it was found from the northern states of the United States to Alaska, and introduced to Australia [6]. It is considered resistant to pollution, oxygen deficiency, and is the only species among the closely related ones present in degraded habitats [5, 6]. It is capable of settling in marshes, and due to their drainage, it has become rare in areas subjected to reclamation. Among European countries, it has a protected status in Ireland (Vulnerable species, VU) [7] and the Czech Republic (Near Threatened, NT) [8]. In general, according to the IUCN Red List 2022, it has the LC status, i.e. the least in need of protection [9].

Currently, Ukraine is home to eighteen species of Sphaeriidae belonging to three genera, namely Musculium, Sphaerium, and Pisidium. Freshwater bivalves are one of the most important components of hydroecosystems, acting as "ecosystem engineers", acting as natural filters and shaping the quality of water in reservoirs. Of course, the main attention of scientists has traditionally been drawn to the largest and therefore most convenient mollusks of the Unionidae family. Some of them can reach up to 250 mm in length, although they usually do not exceed 100 mm. It is known that one individual of this family can filter 200-400 ml of water per hour. Mollusks of the Sphaeriidae family are small (from 1.5 to 22 mm), so they are inferior in their filtration activity. However, since they can have population densities of up to several thousand per square meter, they undoubtedly play an important role in purifying water from particles of biological and mineral origin. They can also serve as food for fish, waterfowl, and aquatic insects. It is important to note that these mollusks, unlike the closely related Unionidae, are hermaphrodites, so they do not need a partner for reproduction and can quickly restore their numbers. At present, we can talk about the catastrophic disappearance of Sphaeriidae species from Ukrainian water bodies and watercourses. In our opinion, this is due to anthropogenic impact and the reduction and disappearance of habitats suitable for these species. The analysis of data on the detection of species of the family Sphaeriidae and their habitat in Ukrainian water bodies allows us to understand the causes of their extinction.

2. Material and methods

The material was based on our own collections of mollusks of the family Sphaeriidae, conducted in 2019-2023 within the northern right bank of the Dnipro River of Ukraine (mainly Zhytomyr-Volyn Polissya) (figure 1, table 1). Information on the collected material was entered into the database [5]. In total, we examined 232 typical habitats. We surveyed large, medium, and small rivers, streams, reservoirs, and ponds. Species affiliation was determined by analyzing



(*a*) (*b*)

Figure 1. Location of the sampling sites (*a*), locations of *M. lacustre* findings (*b*).

Table 1. Information about *M. lacustre* sampling sites.

The sampling site	Sampling coordinates (Latidtude / Longitude)	Population density, ind./m^2	Found with the species
The Sluch River, Nova Chortoria	50.142, 27.4229	1	*S. nucleus*, *S. rivicola*
The Husak River, Levkivka	49.79157, 27.58780	11	-
The Horyn River, Oleksandria	50.84851, 28.05643	3	*S. rivicola*
The Gnilopyatka River, Raiki	50.01399, 28,46017	1	*U. pictorum*, *S. rivicola*
The Gnilopyat River, Khazhin	48.86197, 28.59888	21	*A. cygnea*
The Stavy River, Shchekichyn	50.83117, 28.57828	2	*U. tumidus*, *U. pictorum*, *A. cygnea*, *S. nucleus*
The Khomora River, Polonne	50.09864, 27.68014	1	*U. tumidus*, *U. pictorum*, *A. anatina*, *A. cygnea*, *S. nucleus*

qualitative and quantitative morphological characters [10]. During the collection of material, a 50-100 meter long section of the water body was examined by the route method, habitats typical for the species were selected, where the material was searched for by cleaning the bottom sediments using hydrobiological sieves.

2.1. 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: the experimental mollusks in our study belong to the category of invertebrates, and we ensured that ethical considerations for their welfare were upheld; 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. Results and discussion

The analysis of literary and museum data from the malacological collections of the State Museum of Natural History (Lviv) and the Zoological Museum (Kyiv) allows us to conclude that in the twentieth century M. lacustre was quite widespread in Ukraine (figure 2). Analysis of museum materials allows us to conclude that it was also found in Galicia in the nineteenth century. The species was discovered in the basins of the Dniester, Dnipro, Western Bug, Prypiat, Prut, and was found in the rivers of Crimea and the Azov Sea [5, 11]. According to O. Korniushyn, the species is common to water bodies throughout Ukraine [5]. However, in recent years, there have been increasing reports of the disappearance of this group of aquatic organisms from reservoirs and watercourses due to their anthropogenic transformation and reduction of their

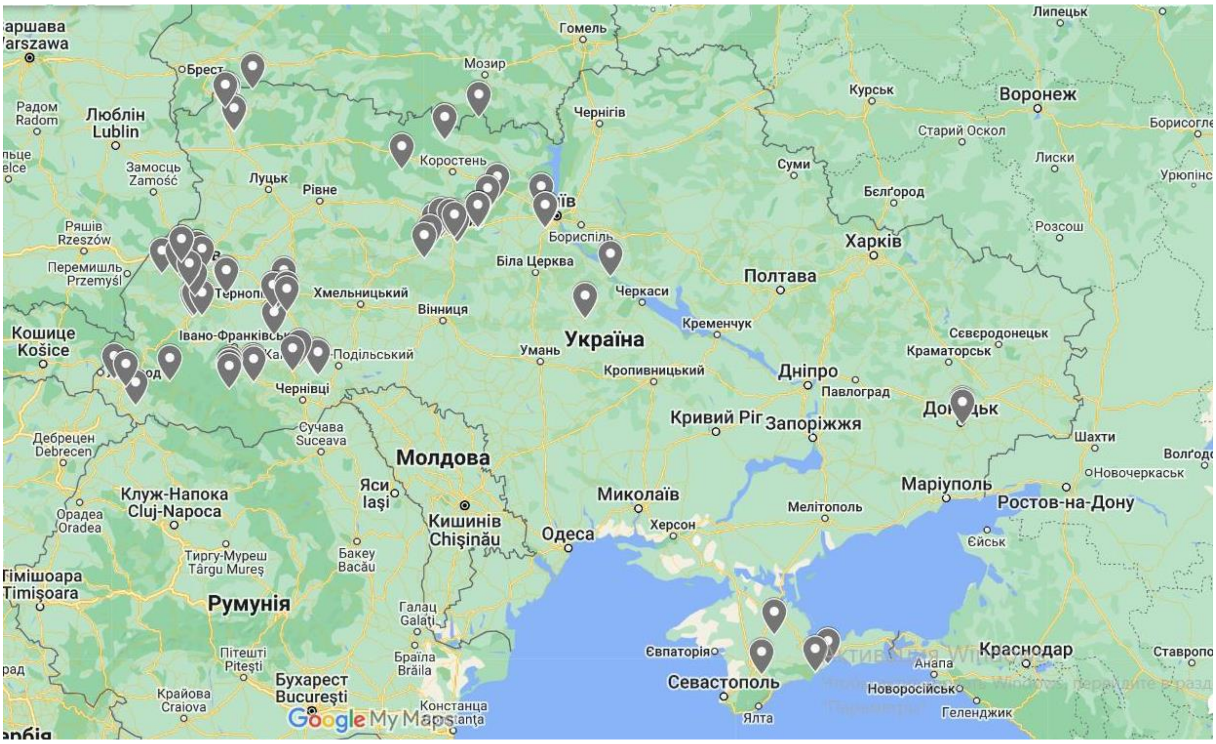
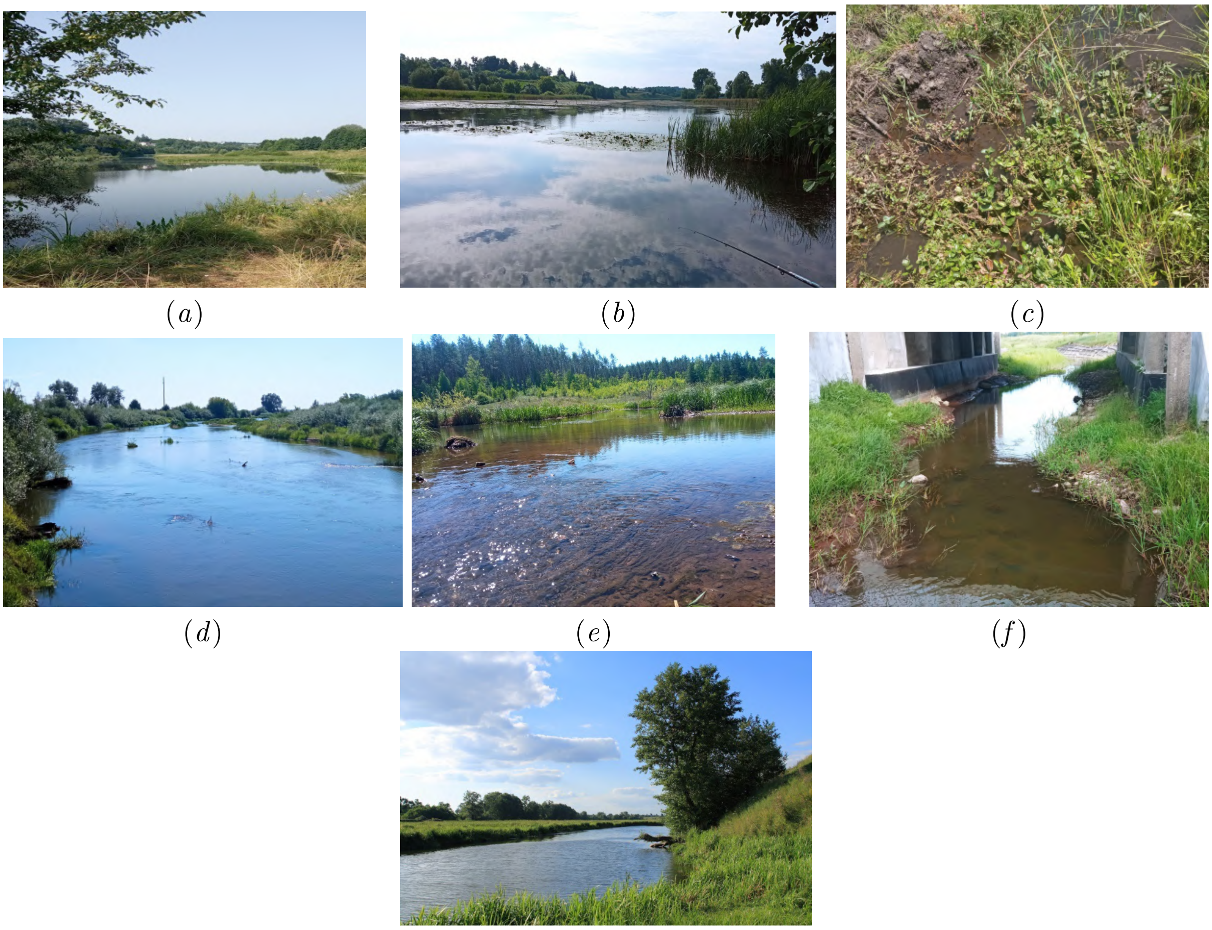


Figure 2. Locations of *M. lacustre* in the nineteenth and twentieth centuries in the river basins of Ukraine according to literature and museum data.

typical habitats [5, 10]. The landscapes of the area under study have also been significantly affected by human activity.

The analysis of the collected materials showed that out of 232 analyzed sampling sites, *M. lacustre* was found in the Pripyat subbasin in only 5 sites, and in the Teteriv basin (Middle Dnipro subbasin) in only 2 sites (table 1, figure 1, figure 3), i.e. its frequency of occurrence in these subbasins is 4% in each, and in general this figure is 3% for the study area. In its habitats, the species was found together with *Sphaerium rivicola* Lamarck, 1818, *S. nusleus* Studer, 1820, *P. obtusale* Lamarck, 1818, *Anodonta anatina* Linnaeus, 1758, *A. cygnea* Linnaeus, 1758, *Unio pictorum* Linnaeus, 1758, *U. tumidus* Philipsson, 1788 (table 1).



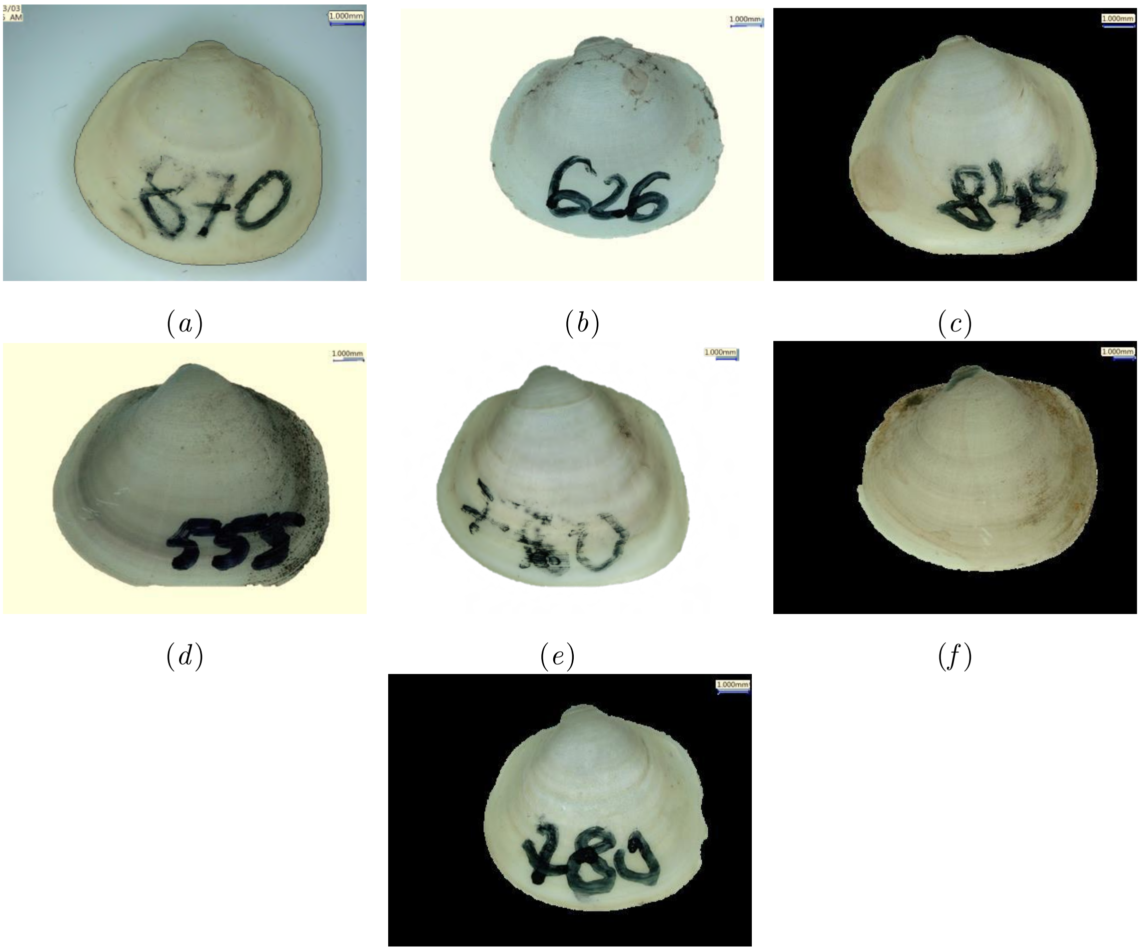
(*a*) (*b*) (*c*) (*d*) (*e*) (*f*) (*g*)

Figure 3. Typical sampling sites of *M. lacustre*: The Sluch River, Nova Chortorya village (*a*); The Hnylopyatka River, Khazhyn village (*b*); The Husak River, Levkivka village (*c*); The Horyn River, Oleksandriia village (*d*); The Hnylopyatka River, Raiky village (*e*); The Stavy River, Shchekichyn village (*f*); The Khomora River, Polonne town (*g*).

The analysis of the collected material allows us to conclude that *M. lacustre* has average size among the species of the family. According to our data, the sizes of the studied individuals are: convexity up to 4.7 mm, height 9.5 mm, length up to 11 mm (table 2). The shell is trapezoidal or rounded-oval, angular, moderately convex, thin-walled, fragile, whitish-yellowish (figure 4). The embryonic part of the shell is separated in the form of a cap (nipple-like elongated), which allows to distinguish this species from other species of the family. At the same time, the shape and

Table 2. Linear measurements of the studied individuals of *M. lacustre*.

Variable	N	Mean	Median	Min	Max	Lower quartile	Upper quartile	Standard deviation
Convexity [mm]	35	3,08	3,0	2,2	4,7	2,8	3,4	0,49
Heigth [mm]	35	5,80	5,7	3,5	9,5	4,4	6,9	1,73
Length [mm]	35	6,82	6,6	3,6	11,0	5,4	8,0	1,94



(*a*) (*b*) (*c*) (*d*) (*e*) (*f*) (*g*)

Figure 4. Shells of *M. lacustre*: The Horyn River, Oleksandriia (*a*); The Khomora River, Polonne (*b*); The Stavy River, Shchekichyn (*c*); The Husak River, Levkivka (*d*); The Sluch River, Nova Chortoria (*e*); The Hnylopyatka River, Raiki (*f*); The Hnylopyatka River, Khazhyn (*g*).

location of this part of the shell varies somewhat in different populations, which is emphasized by other researchers. The surface is smooth and has thin, not evenly spaced spherical arcs. Hinge piates are narrow. The teeth are well defined.

Considered to be a rather eutopian species [11, 12]. We found it in rivers, streams, prefers flowing areas. Avoids heavily silted areas of water bodies. It has never been found in water bodies that are blocked by dams. It has been repeatedly noted as settling in ponds, puddles,

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canals, swamps [11, 12], but we have not found it there. It is concentrated in slightly silted areas, sandy-silt and rocky-silt. It also occurred in areas with more silt (up to about 10 cm), but was concentrated on its surface. It is able to bury itself in silt when water bodies dry out and survive even prolonged (almost up to a year) drying out of the reservoir. It was found exclusively among macrophyte thickets. According to some researchers, it is able to crawl along the stems of macrophytes. The maximum population density was 21 in the Gnylopyat River, 11 in the Gusak River, and 1-3 ind./m^2 in other sampling sites, although according to literature data, in the last century it could reach several thousand per m2 in Ukraine. In total, only 35 individuals of the species were collected and studied.

4. Conclusions

The survey of reservoirs and watercourses in the northern right bank of the Dnipro River in Ukraine in 2019-2023 suggests a significant decrease in the frequency of occurrence and population density of *M. lacustre*. The maximum population density of individuals of the species was 21 in the Hnylopyat River, 11 in the Gusak River, and 1-3 ind./m^2 in other sampling sites. The overall frequency of occurrence in the study area is very low and amounts to only 3%. According to the Red List of European freshwater bivalves, the main reasons for the extinction of these animals are the loss of typical habitats due to anthropogenic transformation of hydroecosystems and pollution. Such changes are caused by the construction of numerous dams, changes in flow velocity and siltation, as well as pollution with wastewater and pesticides. Bivalves are sedentary and require stable habitat conditions. Our analysis of the autecological characteristics of M. lacustre allows us to confirm the information that it is the transformation of watercourses into low-flowing or non-flowing reservoirs that makes it impossible for the species to exist in them. In no case were individuals of the species found in reservoirs, ponds, or dammed river sections characterized by the absence of flow and significant development of muddy bottom sediments; in all cases, the animals were concentrated exclusively in flowing areas.The impact of pollutants on individuals of the species requires further investigation. Further anthropogenic transformation of water bodies can lead to the complete extinction of this species and bivalves in general. There is a need to revitalize rivers, especially small ones, and to develop and implement environmental protection measures.

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Application of the numerical modelling for the interpretation of the piezometric data on earth dams in the view of uncertainties specific for dam operation

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Application of the numerical modelling for the interpretation of the piezometric data on earth dams in the view of uncertainties specific for dam operation

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Abstract. Dam monitoring is an effective method of the management of risk associated with dam operation. Interpretation of monitoring data is an essential part of the monitoring procedure. The main purpose of data interpretation in dams is the well-timed detection of hazardous conditions. Since numerical modelling such as finite element modelling method (FEM) is based on physical equations, it can provide results that can be converted into diagnosis. The application of the numerical modelling for monitoring data interpretation in earth dams in the view of uncertainties specific for dam operation and monitoring is studied with the purpose of obtaining the interpretation results that will be practically valuable for intervention planning. In this study the application of one of the techniques of numerical model calibration for the series of alternative diagnoses for real dam monitoring data interpretation is presented. For reducing the uncertainty, the probabilistic estimations of the alternative diagnoses were inferred with the use of Bayes' rule. The technique applied provides a visually clear representation of the possible diagnosis for the practical decision making.

1. Introduction

As water retaining structures earth dams have application to many industries and serve many purposes from water accumulation to protection from flooding. Due to their specific purpose to resist a big volume of water, dams are a hazard potential. Dam collapse can cause enormous human, economic and environmental losses as it can affect huge territories [1–3].

Seepage is an inherent process constantly present in earth dam body, foundation and abutments. Major part of earth dam failures has been associated with development of seepage related defects [1–5]. Seepage barriers such as impervious core, cutoff wall, diaphragm wall are intended to prevent or slow down seepage. Besides, filters and drainage as "seepage control" measures are implemented. The performance of seepage control components can change over time due to seepage action and aging defects [5, 6].

Monitoring is an effective strategy of providing the dam safety [7–10]. The purpose of monitoring is to provide qualitative and quantitative information for dam performance analysis. Monitoring of the structures covers parameters that technically can be regularly and continuously controlled. In earth dams the traditional controlled performance parameters are piezometric water levels, seepage quantities and settlement. The purpose of the performance analysis in relation to seepage is to assess whether actual seepage situation can ensure the safe operation of the dam. In terms of planning the intervention measures the seepage analysis should also entail the assessment of the effectiveness of seepage barriers and seepage control devices. As far as the assessment of the performance of seepage control devices cannot be concluded directly from the monitoring device readings the proper interpretation of the monitoring data acquires importance.

The application of the methods and techniques of monitoring data interpretation in earth dams in the view of uncertainties specific for dam monitoring and dam behavior are studied. Obtaining the practically valuable interpretation results are in the focus.

2. Overview of the issues in monitoring data interpretation with numerical modelling

2.1. Literature review

Monitoring data analysis, interpretation and consistent explanation of dam behavior is an indispensable step of the structure monitoring [9–12]. In terms of technical diagnostics which is targeted on the practical outputs the interpretation of monitoring data can be also considered as the identification and localization of faults and failures [13, 14]. With the parameters usually controlled in dams the judgement regarding the technical condition of the components cannot be inferred directly from the readings. The aim of the interpretation in this insight is to derive from the monitoring data the estimation of the effectiveness of the performance of the structure components [13]. For dam seepage analysis the structure components are: seepage control members, drainage, soil massifs in dam body and foundation. In this sense interpretation can be considered as diagnosing the technical condition of the separate dam components [10–12].

There are different methods that can serve for data interpretation: deterministic, statistical, artificial neural network approach, probabilistic [7–9]. Since deterministic methods are based on physical governing equations, they provide results that can be easily converted into diagnosis. Among deterministic methods finite element modelling method (FEM) is a useful tool for monitoring data interpretation. It has been gaining more and more practical utility because of the development of high-performance computer hardware as well as software. It is widely used for seepage analysis of earth dams as well [8, 11].

FEM modelling for seepage analysis is based on the Laplace equation. Basic components of the numerical model with FEM incorporate seepage domain geometry, material properties and boundary conditions [6, 8, 11]. In seepage analysis FEM simulates hydraulic heads within the seepage domain including the position of zero pressure line (phreatic line). The zero pressure line corresponds to piezometric water levels that are traditionally monitored on earth dams. In a single simulation the static conditions are considered.

Mismatching of the theoretical groundwater levels provided with FEM and the field piezometric heads can be explained with the fact that actual soil properties differ from design values, spatial properties variance, anisotropy, specifics of boundary conditions, 3D flow effects etc. In the view of the interpretation purpose the deviation (or changing) of material properties that may provide adverse effects for structure performance are also implied. As a means of interpretation FEM modelling enables stepped adjustment of the model with intended changing of the numerical model inputs. This procedure is also known as model calibration [6, 8].

Intrinsically, by its statement and tasks the interpretation is an inverse analysis or inverse problem which in mathematics refers to ill-posed problems [15]. With the multi factor problem, as in the case of seepage analysis, the more factors (or inputs) are involved the more possible solutions are out there. In regards to dams, multiple solutions include numerous combinations of the material properties of dam elements (hydraulic conductivity in terms of seepage analysis) as well as their dimensions that if put together could induce the observed readings.

At the same time, the major disadvantage of the deterministic methods that limits their applicability and reduces the veracity of its simulations for diagnostic purposes is that deterministic methods require the numerous input data which are usually only partially known or have significant spatial variance [6, 11]. Uncertainties from different sources are present in deterministic analysis [9, 10] such as material properties, loading environment, geological and hydrogeological conditions, stochastic uncertainties in monitoring procedures etc. Multiple possible solutions provided during FEM model calibration also increase the uncertainty.

For reducing uncertainties involving the probabilistic approach to results interpretation is required [9].

2.2. Specifics of the monitoring data interpretation in earth dams

Interpretation of the monitoring data with numerical modelling implies model calibration procedure namely the model inputs adjustment so it can reproduce the observed readings. The FEM model calibration procedure can be intricate and ambiguous, and differ according to the considerations behind the purposes. In the insight of diagnostics being aimed at the identification of malfunctioned elements and zones, calibration of the numerical model can be considered as a directed search of the material properties and dimension of dam key elements.

Besides the issue of soils properties variance, the additional complications connected to the particularities of the objects under study (dam and processes) and monitoring methods can be pointed out from the experience of the data processing in earth dams, which are as follows.

Monitoring procedure is based on measurements which are characterized with stochastic variance. Both variance provided by measurement equipment and variance of material properties determining seepage situation bring to the need to not search for the inputs set giving the precise match but to the desired degree of the fit of outputs.

For earth dams commonly hydraulic heads are used as targeted outputs for calibration. Under static conditions the single set of the observed piezometric heads is implemented as targeted outputs of the simulation.

Due to technical limitations with arrangement of monitoring systems in dams there are sections with no measurement equipment that are the monitoring “blind” zones of the dam body with unknown values of performance parameters. For piezometric heads the monitoring “blind” zones usually include the upper shell of the dam body where there are no field data for calibration. Within the upper shell there is often impervious members located as inclined core, concrete protective slabs, other impervious layers that can induce a sharp drop of hydraulic head behind them. The actual position of the phreatic line in such a zone can be predicted through extrapolation or from other considerations. However, the results of the calibration adjustments within such zones can be considered as highly subjective.

On the other hand, the presurmise in the background of the selection of the monitoring data set as the calibration targets can have its impact on the results on calibration. As an example, regarding to the time frame piezometric water levels in all piezometers are observed simultaneously. But then, with deterministic insight, whereas seepage velocities in earth dam are low, changing of piezometric heads doesn’t proceed immediately but with a delay. The presence of the time lag effects in monitoring data also increases the solution uncertainty [16, 17].

In this study we are focused on the investigation of the approaches to FEM model calibration from the view of obtaining the interpretation results that can be used for intervention measures planning in practical decision making. Along with it the implementation of probabilistic estimations to the modelling outputs is considered.

There are different methods of the numerical model adjustment (or calibration of the model) such as iterative adjustment with the use of manual trial-and-error or automated algorithms and sensitivity analysis approach to define the most significant tuning constitutive parameters [8] etc.

The iterative calibration procedure comprises updating of the model inputs in order the model simulations reproduce observed values. Under this approach the single set of monitoring readings (for example, the observed piezometric levels in the given cross section at a certain date) is considered as targeted outputs in all iterations. According to this approach the number of alternative diagnoses comprising different combinations of inputs (or different diagnoses) can be defined that are corresponding to some single position of the observed phreatic line. Since they are producing same outputs, consequently same probabilities of occurrence can be assigned to each of the alternative diagnoses.

One more variation of the iterative approach which can be useful for interpretation purpose implies providing the series of the simulations with different model inputs that refer to the several preliminary defined alternative diagnoses regarding the condition of the dam's key elements [9, 18]. Consequently, there are several simulated phreatic lines as outputs of the modelling which corresponding to several assumed diagnosis.

Fluctuations of the field piezometric water levels define the domain of the possible position of the phreatic line in the range from the upper to lower observed values for reference period. The superposition of the set of the simulated phreatic lines with the domain of observed piezometric water levels provides the visual identification of the possible diagnosis and enables geometric evaluation of the probability of the diagnosis [18]. The set of inputs that brings the phreatic line positioned within the observed interval can be considered as corresponding to the most probable diagnosis. However, as several sets of inputs are simulated, more than one simulated phreatic lines can be located within the observed interval of performance parameter that requires to attribute each of them with the probability of occurrence.

With this approach the issue of time lag effect as well as the issue of the appropriate set of monitoring data selection can be neglected as far as the whole range of observed data is involved in the analysis.

In this study the application of numerical modelling for the series of given diagnoses for real dam monitoring data interpretation is presented. For the probabilistic estimation the Bayesian interpretation of probability can be considered as the most adequate basis for the consistent representation of uncertainties, independently of their sources [6, 9]. With the Bayesian method the a priori probabilities of the structure safety levels provided by experts are combined with the likelihood probability of the monitoring information [19–21].

3. Principles, materials and methods

The real monitoring data is used for the presentation of the interpretation techniques of the monitoring data. The dam under study is located in western Ukraine. The dam is in operation for more than 30 years. The earth dam is 14.7 m high, 7.1 km long with reservoir capacity over 0.1 km^3. It has exposed inclined concrete core and impervious blanket as seepage barriers and the sloped drainage and the drainage ditch with filter layers as seepage control measures. There are sands in the foundation with the local thin layers of peat. Seepage monitoring is provided by operational services on a regular basis. Piezometric water levels and seepage quantities measurements are performed manually in several cross sections of the dam. Monitoring data are provided as time series for the period 2000-2009. The piezometric heads in one cross section are considered for illustration the dam monitoring data interpretation.

FEM seepage modelling was used for piezometric data interpretation. Rocscience RS2 software was used for providing analysis. Since 2D seepage analysis is employed the piezometric heads are used as the outputs.

Considering the structural arrangement of the dam the simulated scenarios include the condition of the key dam's components such as seepage control elements [22]. As tune parameters hydraulic conductivity of the materials and the extent of the seepage control members are used that intended to simulate the presence of the mechanical defects (cracks, unsealed joints etc.) as in the case of impervious structural members or clogging of the filter layers as in the case of drainage zones. For concrete inclined core failure, it is assumed that the possible failure mechanisms may include cracking from uneven settlement and/ or suffusion in filter layers. Reduction of filtering capability of the drainage also relates to seepage. Due to the specific features of the drainage operation mechanical or biological clogging of the exposed parts of the drainage is possible.

For the analysis the following combinations of the effectiveness of the dam components (simulated scenarios) were specified (table 1). Further the simulated scenarios are deemed as diagnosis.

Table 1. Simulated scenarios according to the condition of the key dam's components.

Inclined core condition	Drainage condition	
	Normal	Poor
Normal	Diagnosis 1	Diagnosis 4
Limited effectiveness	Diagnosis 2	Diagnosis 5
Poor	Diagnosis 3	Diagnosis 6

The simulated phreatic lines for the alternative diagnoses are presented on the (figure 1).

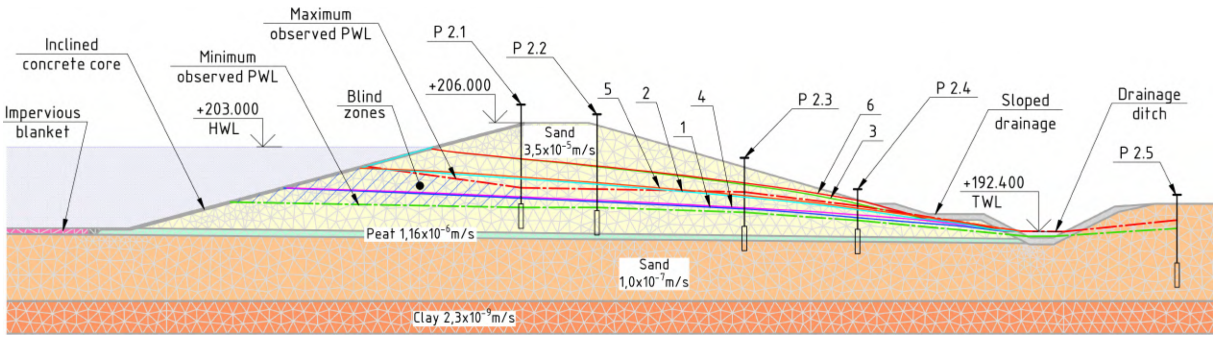

Figure 1. The simulated phreatic lines for the alternative diagnosis.

Since the simulated scenarios are potential, in FEM seepage simulations for all scenarios the normal reservoir water level is assumed as boundary conditions.

The probability of each diagnosis can be defined with two main considerations. The geometric probability implies that the observed value of the piezometric level can be theoretically explained based on material properties and dam zones dimensions. Another consideration is the statistical significance of theoretical explanation based on the historic performance or other knowledge of dam behavior.

The probability of each diagnosis is defined as [18]

$$P(R_i) = P(G_i) \cdot P(D_i)\,. \tag{1}$$

$P(G_i)$ is geometric probability of the location of the simulated phreatic line within the observed domain of piezometric water levels for i-th diagnosis; $P(D_i)$ is probability of the occurrence of the simulated event (i-th diagnosis).

The boundaries of the domain of observed piezometric water levels are based on the data from 4 sensors installed in the same control cross section for the period 2000-2009.

The frequency-based statistics can be used for the assessment of the occurrence probability of the simulated events [1,2,6,18]. For the dams aged from 20 to 50 years the annual probability of failure is estimated to be 0.0038 [1].

Bayesian method of adjustment of the frequency data for site-specific factors is used for this analysis.

The additional considerations like a presence of the symptoms (indirect, visual or instrumental readings) associated with some or other diagnosis can be used for assessment the probability of the diagnosis $P(D_i)$. Two possible symptoms of the diagnoses were considered: the reducing the seepage quantities (symptom k_1) and the cracking of the protective concrete on the upstream face (symptom k_2). Therefore, the conditional probability of the diagnosis with the involvement of the additional statistic information is considered instead namely for the cases of occurrence $P\left(D_i \mid k_j\right)$ or absence $P\left(D_i \mid \overline{k_j}\right)$ of the symptoms k_1 and k_2.

The probability of the diagnosis is computed then with the Bayes' rule for conditional probabilities [9, 21]

$$P\left(D_i \mid k_j\right) = \frac{P\left(D_i\right) \prod\limits_{j=1}^{l} P\left(k_j \mid D_i\right)}{\sum\limits_{i=1}^{n} P\left(D_i\right) \prod\limits_{j=1}^{l} P\left(k_j \mid D_i\right)}. \tag{2}$$

$P\left(D_i\right)$ is prior probability of the diagnosis; $P\left(k_j \mid D_i\right)$ is conditional probability of the occurrence the symptom k_j on objects with diagnosis D_i.

4. Results and discussions

With the use of FEM seepage modelling simulated phreatic lines for the preliminary defined alternative diagnoses were obtained. Simulated phreatic lines for the diagnoses from table 1 are shown on figure 1. Furthermore, the array of the observed piezometric levels for the reference period 2000-2009 is drawn as a domain with boundaries attributed to their maximum and minimum observed values.

The value of the geometric probability is assigned equal to 1 for the simulated phreatic line when it is fully located within the observed domain of piezometric water levels and equal to 0 when it is fully out of the domain. Taking into account the presence of "blind" monitoring zone geometric probability should be reduced according to the "blind" zone extent.

As malfunctioning of two structural members of the dam is assumed with simulated cases (table 1) the prior probability of the diagnosis was computed with the multiplication law as the malfunctioning of the core $\left(P\left(D\left(c\right)_i\right)\right)$ and the drainage $\left(P\left(D\left(d\right)_i\right)\right)$ can be considered independently (table 2).

Table 2. The prior probability of the diagnoses.

Simulated diagnoses	$P\left(D\left(c\right)_i\right)$	$P\left(D\left(d\right)_i\right)$	$P(D_i)$	$P\left(k_1 \mid D_i\right)$	$P\left(k_2 \mid D_i\right)$
D_1	0.85	0.95	0.8075	0.05	0.05
D_2	0.10	0.95	0.0950	0.05	0.10
D_3	0.05	0.95	0.0475	0.05	0.80
D_4	0.85	0.05	0.0425	0.80	0.05
D_5	0.10	0.05	0.0050	0.80	0.10
D_6	0.05	0.05	0.0025	0.80	0.80

With the Bayes' rule (2) the probabilities of each of diagnosis at various combinations of the symptoms are as follows (table 3).

Table 3. The probabilities of the diagnosis at the symptoms.

Simulated diagnoses	$P(D_i \mid k_1, k_2)$	$P(D_i \mid \overline{k_1}, k_2)$	$P(D_i \mid k_1\overline{k_2})$	$PP(D_i \mid \overline{k_1}\overline{k_2})$
D_1	0.249	0.454	0.483	0.880
D_2	0.059	0.107	0.054	0.098
D_3	0.235	0.428	0.006	0.011
D_4	0.210	0.005	0.407	0.010
D_5	0.049	0.001	0.045	0.001
D_6	0.198	0.005	0.005	0.0001

Finally, the probabilities of the diagnosis according to (1) with the geometric considerations are as follows (table 4). As the diagnosis D_3 and D_6 have geometrical probability constituent equal to 0, those diagnosis were not included to the final results table.

Table 4. The probabilities of the diagnosis by equation (1) at the symptoms k_1, k_2 based on monitoring data.

Simulated diagnoses	$P(D_i \mid k_1, k_2)$	$P(D_i \mid \overline{k_1}, k_2)$	$P(D_i \mid k_1\overline{k_2})$	$PP(D_i \mid \overline{k_1}\overline{k_2})$
D_1	0.249	0.454	0.483	0.880
D_2	0.021	0.037	0.019	0.034
D_3	0.210	0.005	0.407	0.010
D_4	0.017	0.000	0.016	0.0004

From the figure 1 two diagnoses could be concluded with almost same geometrical probability. With the involvement of the conditional probability based on statistical information and knowledge of dam behavior the Diagnosis 1 (normal dam condition) can be concluded as the most probable according to the monitoring data for the reference period (table 4). With the inclusion of more site-specific symptoms this technique can become more sound.

The most advantage of the interpretation technique under discussion is that it allows the examination of several diagnoses for data interpretation. Furthermore, it provides the visually clear representation of the possible diagnoses for the researcher or the dam owner, as well as the physical insight of the possible causes of the changes in performance parameters (for this case study the increasing or decreasing of the piezometric water levels). The technique considered is quite illustrative in regards to physical insight of the changing in elements performance to seepage situation that gives the insight of the practical intervention planning. Consideration and graphical representation of the phreatic lines for several alternative diagnoses corresponding to alternative conditions of key dam's elements can serve as visualization of sensitivity analysis for the dam operation personnel.

Along with it, one cannot exclude that the mismatching of the simulated values and field measurements may be not necessarily induced only by deviations or changes of the material properties or dimensions of the key members that was considered in this study as malfunctioning. Changes of the permeability within zones of the dam body can take place both because reducing permeability with clogging and increasing the permeability due to erosion. Those changes not necessarily can cause adverse effects. Nevertheless, they induce the performance changing. Still 3D flow effects can cause the deviation from simulated 2D seepage pattern. The researcher should provide a careful examination regarding what to include in the analysis. The involvment of the historic data and other heuristic approaches can be helpful.

Generally, the main shortcoming of the inverse analysis provided by any calibration method is that the veracity of the results depends on the knowledge of the dam and foundation specific features and understanding of the dam behavior. The experience of the engineers is essential for the inverse analysis.

5. Conclusions

The interpretation of monitoring data is quite challenging as it implicates the inverse analysis with many uncertainties that are an unavoidable feature of earth dam engineering. As a means of interpretation FEM modelling enables calibration of the model with intended changing of the numerical model inputs. However multiple possible solutions provided during FEM model calibration also increase the uncertainty. The numerous uncertainties bring to the need of involving the probabilistic approach into the interpretation problem. The additional uncertainties connected to the particularities of the dam monitoring such as presence of "blind" zones, time lag effects and choice of the required level of accuracy during calibration should also be considered as complications of the interpretation problem.

The application of the techniques of numerical modelling for seepage analysis in real earth dam based on monitoring data is presented. The numerical modelling was performed for several preliminary defined diagnoses. The probabilistic estimations of the alternative diagnoses were inferred based on real dam monitoring data and with the involvement of expert probabilities with the use of Bayes' rule. The obtained estimations enable clearly distinguishing the most probable diagnosis among the alternative ones.

The technique presented can be useful for intervention measures planning in practical decision making for the researchers or the dam owners as it is a quite illustrative in regards to physical insight of the changing in elements performance to seepage situation.

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Regulation of water flow on the foothills on the Ukrainian Carpathians rivers with the use of flooded groynes

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Abstract. Based on the results of extensive laboratory studies of regulatory and protective structures – groynes, carried out in the hydrotechnical laboratory of National University of Water and Environmental Engineering (NUWEE), recommendations for the design, construction, and operation of structures have been developed. The method of hydraulic calculation of groynes is presented. According to these recommendations, a system of structures with experimental types of groynes on the foothills of the rivers of the Ukrainian Carpathians was designed and built. Surveys were carried out on objects of various types of groynes after the passage of floods on the rivers of the specified region. The causes of deformations of buildings and their destruction have been established. The influence of the existing groynes on the channel process has been studied. Conclusions were drawn on the further use of groynes structures as regulatory and protective structures in the foothills of rivers.

1. Introduction

Every year, the problem of the water element becomes more and more urgent, and the need to carry out work on regulating the flow of water on rivers and protecting territories, rivers, and river banks from flooding and erosion is increasing. It should be noted that, usually, floods provoke and intensify other natural disasters, such as landslides, mudslides, tornadoes, possible pollution and contamination of water supply sources, and others [1, 2]. Therefore, damage from inundation by floods ranks second after damage from earthquakes [3].

This topic is especially relevant to the mountain rivers of the Carpathian region. The issue of improving the ecological condition of small and medium-sized rivers in various regions is also relevant. At the same time, it is known that the regulation of rivers is the cheapest and most rational means of influencing natural hydromorphological processes.

On the foothills of rivers, there is a support, which is formed in the channel by random obstacles located in front of the water flow. They change the direction of the flow in this place and cause storm currents to the river bank or to the slope of the protective dam. They are characterized by significant specific flows and slopes of the water surface and erosive flow velocities. Papers [4, 5] describe flow currents associated with a sharp approach to the dynamic axis of the transit flow to the riverbank or the slope of the dam.

Regulation of water flows to protect against natural phenomena can be carried out with the help of low floodable semi-gates located at an angle to the direction of flow.

According to the terminology given in the construction regulations, structures built on the rivers of the Ukrainian Carpathians and designed to protect territories, objects, riverbanks, dam slopes from erosion are called: shore strengthening, protective and regulatory structures. By their majority, they perform protective and regulatory functions for individual local objects of the national economy or territories that need such protection, by regulating the water flow near them.

This paper details the experience of using and operating groynes built from various materials, as such structures are the most common structures among those used as protective and regulatory structures on the rivers of the Ukrainian Carpathians.

As noted by Pysklyvets [6], destructive floods in the Ukrainian Carpathians can be prevented only with the help of systematic hydrotechnical measures (implementing complex regulation), which Austria, Switzerland, and the USA have experience in using. Groynes are one of the main structural elements of the complex regulation of water flows to protect river banks and the slopes of enclosing dams from local erosion.

2. Materials and methods

When performing theoretical and experimental research, we used methods of theoretical and experimental modeling. To confirm the adequacy of the obtained analytical models, generally accepted methods of statistical processing of experimental results were used. In the hydrotechnical laboratory of NUWEE (National University of Water and Environmental Engineering) for a long time, laboratory hydraulic studies of single groynes and their systems were carried out, the methods of which and the results of experiments are given and described in works [7]. Based on theoretical and experimental methods, a methodology for calculating groynes on the rivers of the Ukrainian Carpathians was developed. These methods were improved based on taking into account the main active factors.

The ultimate goal of the experimental research was to write recommendations for the design of coastal protection structures (groynes) designed to protect the bulk banks of rivers and the slopes of longitudinal enclosing and jet-directing dams, which undergo deformations during the passage of floods [7]. The study of the elements of the kinematic structure of the flow near the shore without the installation of groynes and with their presence, as well as the values of the depths of local washouts near the banks of rivers, was the task of this study.

The experiments were carried out on rigid and erosion models of artificial straight and curved channels, and the relative curvature of the channel varied within $R/B=3...5$, where R is the radius of rounding of the channel, and B is the channel width (width between cuts). Model hydraulic studies of built (real-life) regulation objects were also carried out using groynes.

At the same time, the field of actual and averaged velocities was studied on the rigid model, and the erosion capacity of the stream was studied on the erosion model for variants of the channel without structures and with groynes of various structures and parameters.

3. Results

Low groynes refer to active transverse control structures that are designed to protect dams or riverbanks from local erosion by regulating the internal structure of the flow near the structures. Such structures reduce or move erosion away from the bank or levee and reduce the intensity of adverse transverse circulation or change its direction. The choice of the type of the specified structures is carried out based on a technical and economic comparison of the construction options.

Low groynes, if they are placed at an acute angle to the water flow, cause circulation currents in it. Currents lead to a reduction in the danger of flooding and the negative effect of the flow on the shore. In addition, in the bottom area behind the structures, a powerful stationary helix current appears, which captures bottom sediments from the transit flow near the groynes and transports them to the shore. It is such currents that have an increased transport ability to move bottom sediments. The deposition of sediments and their gradual accumulation in the river section near the shore between neighbouring groynes, caused by helical currents, contributes to the sprouting of bushes, trees, and other vegetation, as well as more reliable anchoring of the shore. When using such groynes, the principle of using the flow's internal energy to control the movement of sediments in the desired direction is implemented. An example of such an application of groynes is shown (figure 1).

Figure 1. System of three groynes (gabion structures) to protect the base of the left bank of the Limnytsia River at the approach to the bridge and channel slope of the barrier dam on the Limnytsia River.

The mechanism of interaction of an obliquely located groyne with a water flow is characterized by the following two simultaneous processes that are observed:

- first of all, the peculiarity of the work of the obliquely located groynes is the emergence of a helical current in the form of a vortex roller (local transverse circulation). The vortex originates near the head of the structure, having the greatest intensity of rotation here, and further spreads with the transport of sediments and the gradual attenuation of the circulation. Due to the hydrodynamic structure of the flow in this zone, the current transports an extremely large amount of bottom sediments to the shore. It preliminarily captures them from the transit flow and the erosion pit that forms near the head of the structure. Thus, over time, there is a gradual accumulation of sediments near the beginning of the structure and in the area between the adjacent groynes, which contributes to the provision of reliable protection of the river bank or the slope of the dam from erosion by the water flow (figure 1);

- secondly, the work of an obliquely located groyne consists of creating secondary currents (general transverse circulation), which organize the movement of the flow in the desired direction over the entire width of the groyne. Such a circulation arises and manifests as a result of the deflection of surface currents, which flow from above over the groyne and try to get into the lower part of the building normal to its longitudinal axis. They (surface currents) receive and keep trajectories directed from the shore in the direction of the transit part of the water flow. As a result of the interaction of the surface and bottom currents flowing around the groyne, a pressure gradient appears in the compressed part of the channel, which directs and organizes the movement of bottom currents over the entire width of the groyne toward the shore. It is the bottom currents that transport the sediments to the river bank or the slope of the dam.

The direction of average vertical velocities must be known in the design of the structure, which, in the absence of data, can be determined by constructing a flow plan. Taking this plan into account, they carry out the optimal arrangement of groynes.

Based on the conducted experimental studies, a methodology was developed for the calculation of obliquely located groynes to protect river banks and dam slopes from erosion.

The parameters of low and obliquely located groynes can be determined as follows:

- The angle of the location of the groynes. The location of individual groynes in the plan is characterized by the angle between the axis of the groynes and the direction of the river flow near the structure α. Groynes should be placed upstream in such a way that the angle α is within 50-60^0.
- The height of the groynes. The average longitudinal height of the groynes P for the foothill sections of the rivers, calculated from the limit water level with a probability of exceeding 95%, should be taken equal to $P = (0.5 - 0.6)H$, where H – the average depth of the water flow, m.

Then the mark of the top of the groynes in the middle of the structure will be $\downarrow TG$=$\downarrow TQ$(95%)+ P. The mark of the crest of the groynes near the head and root is determined taking into account the slope of the crest of the structure, the value of which is recommended to be taken within $i_s = 0.01 - 0.02$.

In areas of rivers with severe ice conditions, the height of the groynes must satisfy the requirements that during the ice retreat, the thickness of the ice t_i passes over the groynes. That is $P < H_i - t_i$, where H_i is the depth of the water flow during the ice advance.

Taking this into account, the height of continuously flooded groynes for the conditions of foothill sections of mountain rivers should be no more than 1.0 m. Recommendations for the design of groynes are given in [6,14,15,18].

The length of the groyne, l, should be determined so that the planned compression of the river flows with a width of B is within $lsin\alpha/B = 0.2...0.4$, $l'/B = 0.2...0.4$, and the ratio of the projection of the groyne l' to the height of the groyne P is within $l'/P = 21...35$. Here there are B – this is the width of the river flow in the area where the structures will be installed. The length of the structure is recommended to be within $0.1 - 0.3$ of the width of the stream – $l' < 0.3B$, while its length should be $7 - 15$ of its height. Its minimum length should meet condition $l(min) > m_1 h_p + a_0$, where $m_1 = 1.2...2.0$ is the coefficient of laying the slope of the erosion gap near the head of the groyne; h_p – the depth of the erosion gap near the head of the groyne; $a_0 = 2..3$ m – margin in the length of the structure; l' – projection of the length of the groyne on the normal to the direction of the flow near the groyne.

The distance between adjacent groynes on straight sections, as well as on slightly curved sections, is taken to be 200 m – for medium and large rivers, and 70-150 – for small rivers. The recommendations of I. L. Rozovskyi [8] should be used for determining the bottom velocities and their direction when locating groynes on a meandering riverbed.

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Determining the planned position of groynes, their sizes, types, and sizes of bottom and bank (slope) fastenings is carried out by using experimental data on the fields of instantaneous bottom velocities and specific flows. They determine the erosion capacity of the river flow near the groynes. The calculation of the fastening of the bank of the river bottom or the slope of the dam near the structure can be performed in the following order.

First, the value of the maximum specific flow is determined near the head of the groyne

$$\left(\frac{q_{\max}}{q_0}\right) = [1.44 - 0.353\,(\alpha - 90)]^2 \left(0.82 + 0.46\frac{P}{h} + 4.65\frac{\Delta}{h}\right), \tag{1}$$

where q_0 and $q_{\max}$ – the specific consumption of domestic sewage in the area of the groyne and the maximum at its head; $\frac{\Delta}{h}$ is the relative height of roughness protrusions.

In the case of erosion of non-homogeneous non-cohesive soils, flow velocities are allowed, taking into account the formation of self-wetting. In this case, the permissible non-eroding speeds are approximately equal to 75% of the permissible non-eroding speed for large soil particles, which should be no more than 10%. Based on the known values of the maximum specific flow and the permissible non-eroding speed, the maximum depth of the flow when washing the bottom is established.

$$H_B = \frac{q_{\max}}{v_H}, \tag{2}$$

where v_H is the non-washable speed.

Then the depth of the erosion gap itself will be equal

$$h_b = H_B - h. \tag{3}$$

The distance from the intersection of the axis of the groyne with the end face of the head of the groyne to the place of maximum erosion of the bottom a is determined by the formula

$$\frac{a}{P} = \left[4 + 5.56(\alpha - 90)^2\right] \left(2.7A\frac{B}{45^\circ} + 1\right) \left(1.61 - 1.53\frac{P}{H}\right). \tag{4}$$

The maximum width of the flexible mattress is determined from the considerations of its coverage of the slope of the erosion gap with some margin according to the formula

$$b_T = \sqrt{\left(a - \frac{\tilde{b}}{2}\right)^2 + P^2 + K}, \tag{5}$$

where $\tilde{b}$ is the width of the head groynes along the bottom; $K = 1...2m$ – margin in the width of the mattress attachment of the bottom is set depending on the value of the maximum bottom instantaneous velocities of one-percent coverage near the head of the groynes, which are determined by the formula

$$\frac{v_{1\%}}{v} = \left[0.85 - 0.115\frac{l'}{l - l'} + \left(0.0182\frac{l'}{P} - 0.1\right)\frac{\alpha}{\pi - \alpha}\right] \sqrt[6]{\frac{h}{P}} \left(1 - \frac{a}{P}\right) + 1.215\left(1 - \frac{\Delta}{h}\right)\frac{a}{P} \tag{6}$$

The size of the upper layer of stone of the bottom mattress is determined by the formula of M. M. Biliashevskyi $d_k = 0.0067v_{1\%}^2$ [9]. To obtain a stable fastening, the found diameter of the stone should be multiplied by the stock factor of 1.2÷1.4. If the size of individual stones in the overburden is too large at high flow speeds near the groyne, then the upper layer of the bottom mattress outside the structure should be made of interconnected concrete slabs. Unenforced groynes can be more reliable and easier to operate than mattress-rigged groynes if their soles are sunk below the mark of expected bottom erosion. The expediency of such a design is greater, the smaller the expected erosion of the bottom.

The type of mattress reinforcement of the shore near the groyne can be selected according to the value of the instantaneous (actual) speed of one-percent security within the shore or slope along the groyne, which is determined by formula

$$\frac{v_{\max}}{U_O} = \left(\sqrt{\frac{\alpha - 13}{408}} + 1\right)(0.74 + Fr)\left(0.72 + 0.61\frac{P}{h} + \frac{1}{0.115}\frac{\Delta}{h}\right)\left(1 - \frac{a}{P}\right) + 0.342\left(1 - \frac{\Delta}{h}\right)^{0.7}. \quad (7)$$

4. Analysis of the operation of groynes on the rivers of the Ukrainian Carpathians based on the results of field studies

Starting in 1957, a significant number of groynes of different designs were built on the rivers of the Ukrainian Carpathians. According to the design features and functional purpose, the most common types of groynes are: type 1 – deaf high (non-flooded) groynes; type 2 – low flooding groynes; type 3 – combined groynes (consisting of a deaf and lowered part); type 4 – through groynes.

Different types of groynes can be made of different materials, namely: concrete blocks, gabions (figure 2), reinforced concrete blocks, stone, soil (temporary structures). Such structures are arranged to protect the slopes of enclosing dams and the ground surface of mountain highways, river banks and the foundations of dams. They reduce the speed of the water flow, reduce or change the intensity of adverse transverse circulation, ensure the accumulation of sediments near the banks or slopes and, thereby, protect the main regulatory structures or river banks from erosion.

Low, continuous flooded groynes, compared to blind groynes, have proven themselves well in work, because they interact "softer" with the water flow, which leads to less erosion of the bottom near the structure. They also reduce the possibility of erosion of the opposite bank or slope and are less affected by the ice flow. Even when they are located against the flow, they can regulate the regime of sediments, accelerating the introduction of sediments and siltation of the space between neighbouring structures. Thus, at the same time, they strengthen and protect the river bank (dam slope) from possible erosion and damage. Currently, the following types of low flooded groynes are used in the foothills of the rivers of the Ukrainian Carpathians: groynes made of massive reinforced concrete blocks measuring (2.0x1.0x0.5) m or gabions, which are placed on brushwood and stone mattresses with a thickness of 0.35...0.5 m; tuff-free cellular groynes; groynes made of massive shaped blocks with metal (hinged) joints.

In recent times, groynes made of oversized stone are more often practiced, which justify themselves in work, and work reliably, thanks to the significant weight of each stone, they can resist the erosion ability of the stream. Therefore, they perform a protective function. During the operation of low submersible groynes, during their operation in a submerged state during the passage of floods, regardless of their design (and material), the following modes of operation can be distinguished: 1) flow around a single groyne, located facing the water flow; 2) flow around the system of groynes, also located upstream.

The following conclusions can be made based on the results of field observations of the operation of low groynes made of concrete reinforcement blocks or gabions:

- the operation of such groynes is effective at the initial stage of their operation until the metal elements of the connection are not broken;
- the groynes works effectively as long as its design (plan and height) position in the structure is preserved;

Figure 2. System of short fortifications of the river Siret, Storozhynets district, Chernivtsi region.

- in the most difficult hydraulic conditions, the first groyne located in the system, which first meets the water flow, and the last groyne in the system, which does not have additional water support, work; as a result of this arrangement, these two demigods experience the greatest disturbance or destruction;
- an erosion is formed near the head of each groyne, the depth of which must be determined at the design stage;
- after the passage of the next flood, the condition of each groyne should be examined and, if necessary, the necessary repairs should be carried out.

5. Conclusions

On the rivers of the Ukrainian Carpathians, various regulatory and protective structures are used: barrier and flow-directing dams, dams, groynes, traverses, longitudinal shore fortifications, etc. Based on the theoretical and experimental methods, a methodology for calculating reefs on the rivers of the Ukrainian Carpathians was developed. These methods were improved based on taking into account the main active factors. Also, the advantages and disadvantages of these structures were determined based on the results of multi-year field surveys of their operation. The problematic elements of the construction, which require further laboratory research, have been identified. Surveys were carried out on objects of various types of groynes after the passage of floods on the rivers of the specified region. The causes of deformations of buildings and their destruction have been established. It was determined that the first and last groynes of the system are subjected to the greatest load in the system, which includes several groynes, so they need periodic repair. During the repair of groynes (restoration of the main parts, extension, and formation of the groynes, etc.), it is necessary, first of all, to identify the cause that led to the destruction of the main structure, and then carry out repairs.

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Analysis of the impact of water use and consumption for a nuclear power plant on alterations in the hydrological and temperature regimes of a river: A case study

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Abstract. Hydrological indicators are important in shaping the ecological status and economic potential of surface water bodies. Industrial facilities that consume water can change the hydrological and temperature regimes of water bodies. The purpose of this study was to investigate the impact of water use and consumption for the Rivne Nuclear Power Plant (RNPP) on alterations of indicators of the hydrological and temperature regimes of the Styr River. The study revealed patterns of changes and analyzed the hydrological indicators of the Styr River under water use and consumption by the RNPP, and the temperature regime of the Styr River in the RNPP impact zone, revealed patterns of dynamics of water use and consumption for the RNPP, determined the correlation between the Styr River discharge and the RNPP water discharge in the hydrological regime of the Styr River. The range of variability approach was used to assess of the Styr River hydrological alteration in the RNPP impact zone. During the warm seasons of 2019 and 2020, the Styr River experienced periods of low water flow. A strong positive correlation ($r = 0.7 - 0.9, R^2 = 0.7623, p < 0.0001$) was found between water use and consumption at RNPP and the temperature of Styr River water. Additionally, a very strong positive correlation ($r = 0.9934, R^2 = 0.9869$) was found between the temperature of Styr River water before and after discharge. Furthermore, it is observed that during the warm season, there is an increase in water consumption and discharge costs for RNPP. Thus, the results of the study indicate that there is no impact of RNPP water discharge, and therefore no measures to improve the condition of the Styr River are required.

1. Introduction

The implementation of the Water Framework Directive (WFD) [1] provides a legal framework for the sustainable management and protection of freshwater resources. The WFD states that the "good" ecological status of surface water bodies should be achieved. To determine the ecological status of surface water bodies, hydrological, chemical and physico-chemical indicators should be taken into account. Chemical and physico-chemical indicators of surface water bodies can be determined using actual concentrations of pollutants [2]. Hydrological indicators represent the established hydrological regime, the good ecological status of which is achieved when the quantity and dynamics of runoff are in balance, reflecting undisturbed conditions [3]. Thus, improvement actions are required where hydrological indicators affect the ecological status of surface water bodies and impede the achievement of WFD objectives. According to the WFD Reporting Guidance [4] , hydrological alteration is considered as an impact on habitat change, i.e. indicators of the current hydrological regime. Therefore, determining the actual hydrological regime is important in terms of establishing a baseline for further assessment of anthropogenic pressure on water bodies. Changes in the hydrological regime can lead to erosion or deposition of sediments, potentially affecting the riverbed and the habitats of aquatic organisms. The basis for the alteration of the hydrological regime is to determine changes in the current hydrological indicators of water bodies. In particular, the most commonly used hydrological indicators for assessment of hydrological alteration are: the average annual flow – Q_a, the average daily flow – Q_d, the average monthly flow – Q_m, the average annual low flow – Q_{al}, the average annual maximum flow – Q_{dl} [5]. However, the assessment of hydrological alteration is carried out by the range of variability approach (RVA). The RVA requires an assessment based on differences in the characteristics of the flow between two defined periods. The RVA approach uses a simple three-class system of equal range of hydrologic alteration: low 0–33%, moderate 33–67%, and high 67–100% [5, 6].

The assessment of hydrological alteration is important for the river basin, as it solves the problem of identifying loads and minimizing the impact of human activity on the environment. Thus, in order to minimize the anthropogenic impact on hydrological alteration, it is necessary to understand the mechanisms of its consequences, in particular, the flow of significant volumes of industrial water discharges into the river. The operation of an open recirculating power plant is connected with the use of large quantities of water that is intake and discharged into a water body. Continuous withdrawal of water can reduce a water body, potentially affecting aquatic ecosystems and water quality. Water discharge from an open recirculating power plant can reach up to 1.0 m^3/s per 1000 MWh of electricity generated, containing residual heat removal and chemical compounds [7]. Additionally, the combination of temperature effects with a large quantity of water flow can affect the hydrological indicators of a water body. Continuous discharge of treated but potentially contaminated water from an open recirculating power plant can contribute to water quality issues, affecting downstream water users and ecosystems. Thus, the assessment of hydrological alteration of a water body under industrial water discharge requires an integrated approach, taking into account operational and environmental aspects. In summary, the water use and consumption associated with nuclear power plants can have considerable impacts on the hydrological and temperature regimes of rivers. Careful consideration, monitoring, and implementation of mitigation measures are crucial to balance the need for energy production with the preservation of aquatic ecosystems and water quality. The practical significance of the study is that the results obtained can be used for planning and implementing WFD in the area of non-radioactive influence of nuclear power plants. It is worth noting that while there have been no recent systematic studies investigating the impact of NPP water usage on the hydrological regime of water bodies, including rivers, we can confidently state that this is an area of ongoing research. It is important to approach this topic, acknowledging the need for investigation.

The purpose of this study was to investigate the impact of water use and consumption for the Rivne Nuclear Power Plant (RNPP) on changes indices of the hydrological and temperature regimes of the Styr River.

2. Methodology and methods of research

The object of research is the hydrological alteration and water temperature of the river in the zone of water use and consumption of the RNPP under the influence of discharge of return water from an open recirculating system. The methodology of this study was to determine the flow of water use and consumption for RNPP and the Styr River water flow in the RNPP impact zone. This study used the daily flow monitoring results for the period 2018-2022, carried out by the RNPP hydrological post on the Styr River below the RNPP intake, located within the urban area of Varash figure 1. Water flow measurements were carried out using standard measurement methods (ultrasonic meters and diaphragm-type instruments). The flow velocity was measured using an acoustic flow meter, and the flow was calculated as the product of the cross-sectional area (m^2) and the average flow velocity (m/s). The temperature of natural and processed waters was measured according to [8]. Statistical processing of the study results involved determining the range of data series (min-max), arithmetic mean (M), standard deviation (± SD), and coefficient of variation (CV) of the corresponding sample using the BioEstar software package (Version 5.3, MLM). The analysis of the data set to assess the relationship between the variables of the control results was performed using the Pearson correlation coefficient (r) and the significant influence (p) and the coefficient of determination (R^2) [9]. The hydrological alteration (G, %) in the Styr River study area was calculated for hydrological indicators: $Q_a, Q_d, Q_m, Q_{al}, Q_{dl}$, according to formula.

$$Gn = (Q_n - Q_{n+1}) \cdot 100/Q_n \tag{1}$$

were Q_n – the flow for the previous year (2018, 2019, 2020, 2021) or month (January-December) depending on the hydrological indicator, m^3/s; Q_{n+1} – the flow for the following years of the study (2019, 2020, 2021, 2022) or month (February-December) depending on the hydrological indicators, m^3/s.

3. Results

The RNPP has four power units with a water-powered energy reactor with a total capacity of 2835 MWh, built in the 1980s. The RNPP has an open recirculating system with cooling towers, and water is constantly being intake and discharged into the Styr River (right tributary

Figure 1. The scheme Styr River water intake and discharge for the RNPP (1 – site of the RNPP; 2 – Styr River; 3, 4 – water intake; 5 – return water discharge; 6 – hydrological post).

of Pripyat (Dnieper basin). The Styr River basin is located in the north-west of Ukraine, within the Lviv, Volyn and Rivne regions. The river is 494 km long and covers an area of 13100 km^2, with an average annual water flow of 49.5 m^3/s at the mouth, narrowing to 10-20 m in the upper reaches and widening to 30-50 m in the middle and lower reaches. The bottom of the riverbed is composed of sandstones and shales of Cretaceous and Paleogene age, and in the lower reaches – Miocene clay deposits. However, according to the surface water typology, the Styr River is a lowland, sandy loamy river [10].

In particular, the Styr River water flow (D) during monitoring at RNPP hydrological post varied in the range (min-max) from 10 to 63 m^3/s, M = 27 m^3/s, SD = ± 18 m^3/s, CV = 51.36 %. In addition, the water temperature of the Styr River (T) during monitoring at RNPP hydrological post varied in the range (min-max) from 0.3 to 24.6 °C, M = 12.6 °C, SD = ± 8.7 °C, CV = 77.12 %. Thus, before and after the RNPP discharge, the Styr River water temperature has increased by up to 1.11 °C in the summer season and by up to 2.07 °C in the winter season. The established limit for the increase in water temperature, according to the terms of the RNPP special water use permit [11], should not exceed 3 °C. Therefore, the actual difference in water temperature of the Styr River before intake (T intake) and after discharge (T discharge) for 2018-2022 does not exceed the established limit and is an average value of 1.07 °C, SD = ± 0.64 °C, CV = 73.55 %.

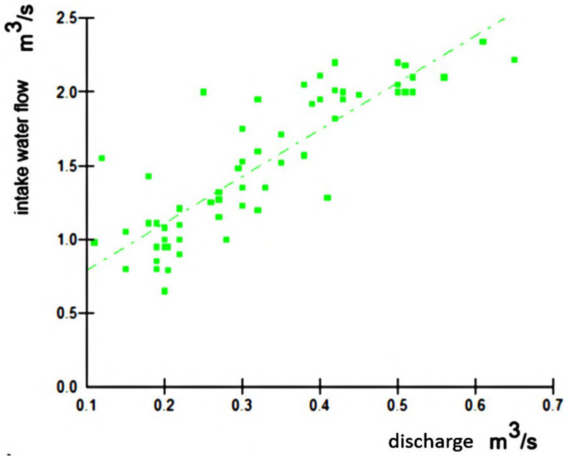
In particular, the flow water intake (MU) RNPP varied in the range (min-max) from 0.8 to 2.4 m^3/s, M = 1.48 m^3/s, SD = ± 0.51 m^3/s, CV = 27.92 %. In addition, the flow discharge return water RNPP (BD) varied in the range (min-max) from 0.15 to 0.67 m^3/s, M = 0.31 m^3/s, SD = ± 0.22 m^3/s, CV = 45.63 %. The correlation between the Styr River water temperature values before and after the discharge is positively significant ($p < 0.0001$) at the very strong level ($r = 0.9934$) and is determined by $R^2 = 0.9869$ (figure 2, table 1).

The magnitude of Styr River discharge does not correlate significantly with temperature (figure 2, table 1), while the maximum Styr River discharge formed either from meltwater during spring high water or as a result of extensive rainfall. Indeed, the water temperature of the Styr River is influenced by the flow intake and discharge of RNPP water, because it is observed a positively significant ($p < 0.0001$) at a strong level ($r = 0.7 - 0.9$) correlation between the flow intake and discharge RNPP water and the water temperature of the Styr River(figure 2, table 1).

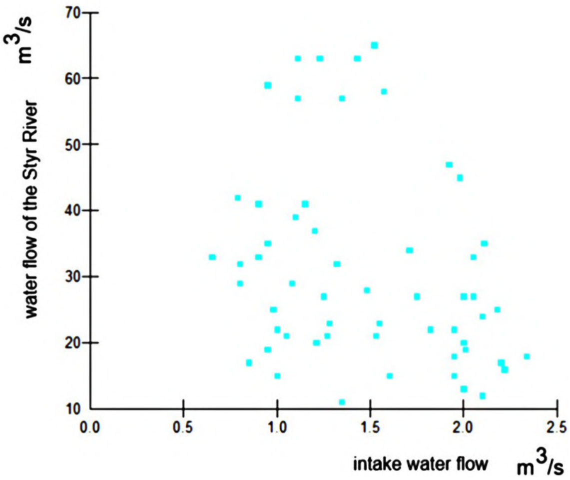
The decrease in the river flow with the increase in the amount of water discharged to the river by the RNPP (figure 2 e) is not related, as the discharge is only 10 per cent of the river flow. The higher water discharged and discharged (figure 2 e,f) to the river is due to the technological mode of operation of the open recirculating power plant and is observed during the warm season, when the river flow is minimal.

The magnitude of the hydrological alteration of the Styr River by $Q_a, Q_{al}, andQ_{dl}$ using RVA in 2018-2022 are characterized as low and moderate (table 2), and by Q_d, Q_m in 2018-2022 are characterised as low (table 3). This suggests that the alterations in the Styr River's hydrology for components Q_a, Q_{al}, and Q_{dl} are within a range considered acceptable or moderate. However, the term "low" suggests that the impact might be minimal for some components, while "moderate" indicates a more noticeable but still manageable level of alteration. For Q_d and Q_m, the characterization is consistently low. This implies that alterations in these components are minimal and likely have a limited impact on the hydrological regime of the Styr River.

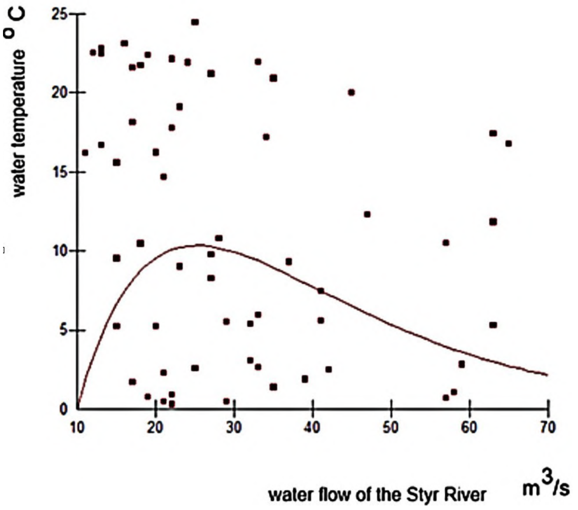
In particular, $G(Q_a)$ by module for the Styr River in the RNPP impact zone varied in the range (min-max) from 3.7 to 16.2 %, $G(Q_{al})$ min-max from 8.3 to 31.5 %, $G(Q_{dl})$ min-max from 9.5 to 46.1 %, $G(Q_d)$ min-max from 2.2 to 28.6 %, $G(Q_m)$ min-max from 2.2 to 32.4 % (table 2, table 3). Statistical indicators by module of hydrological alterations for the Styr River in the RNPP impact zone (figure 3) show the largest variations for the maximum values of the flow (Q_{dl}), the smallest variations are observed for the annual flow (Q_a). Therefore, this suggests



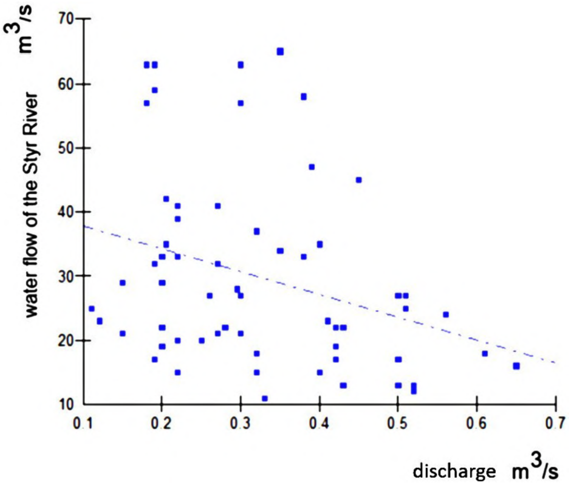
(a) – RNPP intake and discharge flow



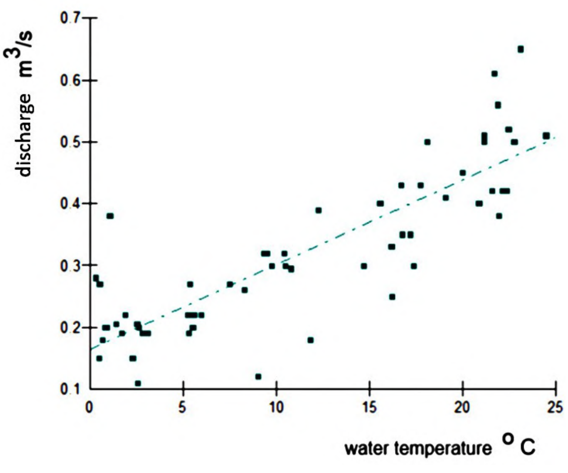
(b) – Styr River and RNPP intake flows



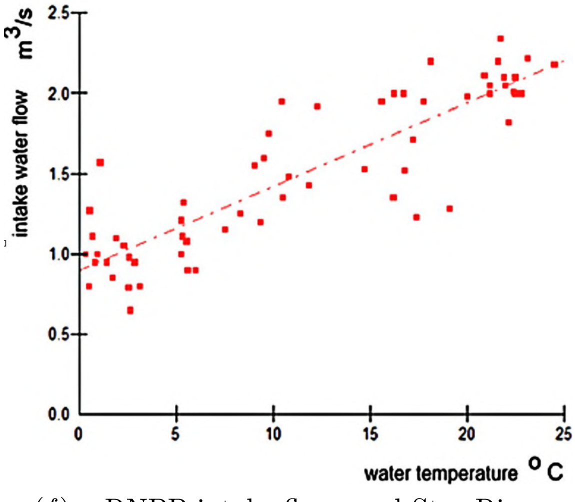
(c) – Styr River and RNPP discharge flows



(d) – Styr River temperature and flows



(e) – RNPP discharge flows and Styr River temperature



(f) – RNPP intake flows and Styr River temperature

Figure 2. Correlation of observed flow data of the Styr River and RNPP sites.

Table 1. Characteristics of correlations between hydrological indicators and water temperature of the Styr River.

Indicators	T intake	T discharge	D	MU
		$r(p)$		
T intake	1.0000 (<0.0001)	–	–	–
T discharge	0.9934 (<0.0001)	1.0000(<0.0001)	–	–
D	-0.2616 (0.0434)	-0.2433 (0.0609)	1.0000 (<0.0001)	–
MU	0.8731 (<0.0001)	0.8657 (<0.0001)	-0.3154 (<0.0001)	1.0000 (<0.0001)
BD	0.8524 (<0.0001)	0.8327 (<0.0001)	-0.3125 (<0.0001)	0.8569 (<0.0001)
		R^2		
T intake	1.0000	–	–	–
T discharge	0.9869	1.0000	–	–
D	0.0685	0.0592	1.0000	–
MU	0.7623	0.7494	0.0995	1.0000
BD	0.7267	0.6934	0.0976	0.7342

Table 2. Calculation results of the hydrological alteration of the Styr River (breakdown of years).

Year	Hydrologic indicators, m^3			Hydrological alteration, %		
	Q_a	Q_{al}	Q_{dl}	$G(Q_a)$	$G(Q_{al})$	$G(Q_{dl})$
2018	804168000	504576000	1829088000	–	–	–
2019	834470000	426666555	1586768000	-3.7	-22.9	-43.7
2020	748980000	346896000	1103760000	10.2	8.3	46.1
2021	870393600	378432000	2049840000	-16.2	25.0	-12.1
2022	963740160	409968000	1797552000	-10.7	31.5	9.5

that, among the hydrological parameters studied, the maximum flow Q_{dl} exhibits the greatest variability over the analyzed period and Q_a over the analyzed period, the overall yearly flow pattern remains relatively stable. Minimum values by module for $G(Q_a)$ and $G(Q_{al})$: 3.7 and 8.3 for the Styr River in the RNPP impact did not follow the normal distribution of the data (figure 3).

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. 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 at 25 °C level decreases to 7.5-8.0 units, and in summer it increases up to 7.8-8.5 units and are determined by the equilibrium of the carbonate water system [12].

4. Discussion

The analysis of the dynamics of the Styr River hydrological regime shows a characteristic phase of increasing flow in the spring flood every year, which confirms the historical data on the Styr River water flow [10]. Considering that the river is nourished by both melting snows and rains, it is not unexpected. Nevertheless, the low water flow can lead to serious consequences of limiting

Table 3. Calculation results of the hydrological alteration Styr River (breakdown of months).

Month	Hydrologic indicators, m^3		Hydrological alteration, %	
	Q_d	Q_m	$G(Q_d)$	$G(Q_m)$
January	3006720	93208320	–	–
February	3144960	88058880	-4.5	5.5
March	3818880	118385280	-21.4	-32.4
April	3732480	115706880	2.2	2.2
May	3386880	101606400	9.2	12.1
June	2557440	79280640	24.4	21.9
July	1823666	56922456	28.6	28.2
August	1365866	39104640	25.1	-31.3
September	1503360	45100800	-10.0	-15.3
October	1845602	56258555	-22.7	-24.7
November	2108160	63244800	-14.2	-12.4
December	2298240	71245440	-9.0	-12.6

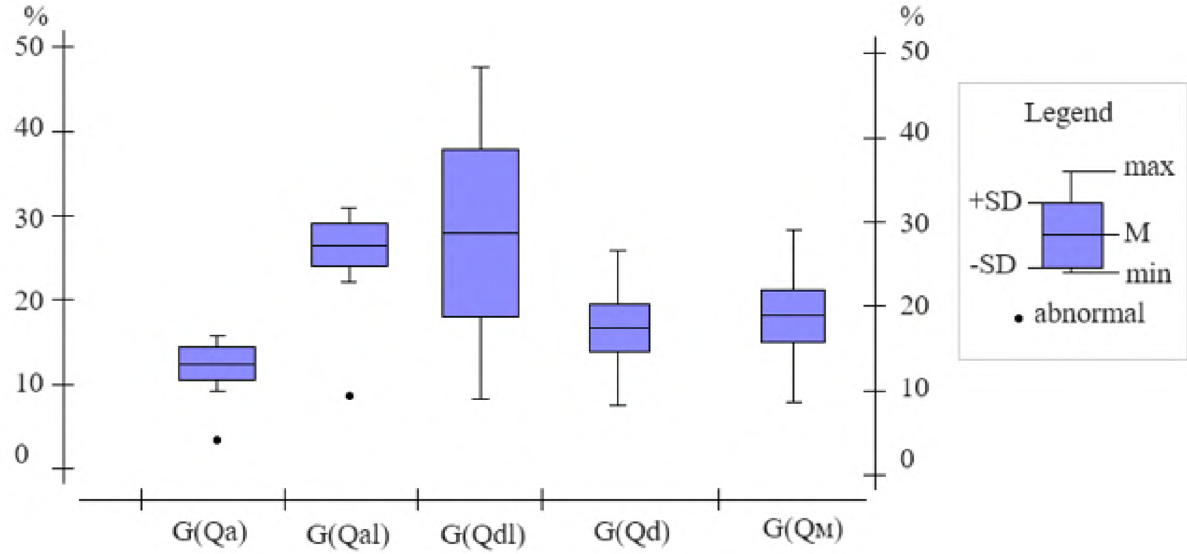


Figure 3. Statistical indicators by module of hydrological alterations for the Styr River in the RNPP impact zone.

the water supply to the power plant and negative environmental impact on aquatic ecosystems. Under the terms of the RNPP special water use permit [11], the flow limit is 8 m^3/s, below which it is prohibited to withdraw water from the Styr River. The actual Styr River water flow for 2018-2022 in the RNPP impact zone did not decrease below the normalised limit flow. Therefore, the recorded moderate hydrological alterations of the Styr River according to $G(Q_{dl})$ obtained in 2019 and 2020 may be associated with natural factors, namely an increase in the Styr River flow in spring floods and a decrease in the flow in the warm season. The water temperature dynamics in the Styr River are expected to show a seasonal increase during summer and a decrease during winter, as hypothesized by the authors. In the controlled areas before the water intake and after the RNPP water discharge, an increase in the temperature of the Styr River water due to the

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RNPP water discharge is observed, and the temperature effect of the return water discharge does not exceed the limit according to [11].

Heat removal in a power plant's open recirculating system leads to evaporation and requires constant addition of make-up water and discharge of return water [10]. However, the water intake flow for RNPP needs, according to the terms of the RNPP special water use permit [11], should not exceed the intake flow limit of 2.79 m^3/s, and the return water discharge should not exceed the flow limit of 0.7 m^3/s. In practice, the actual water intake and discharge flows of the RNPP open recirculating system for 2018-2022 did not exceed the limits. Thus, an increase in water consumption of cooling systems is observed in the warm season, which is associated with an increase in ambient temperature and, accordingly, greater evaporation of water [7], as evidenced by the correlation dependencies obtained figure 2.

The moderate hydrological alteration ($G = 33-67\%$) for the Styr River was recorded in 2019 and 2020. In general, the significance of Qd and Qm for the Styr River in the RNPP impact zone for 2018-2022 is characterised as low, since the obtained RVA values do not exceed 33 % table 3. Thus, the values of $G(Q_m) = 32.4$ and 31.3 % of the Styr River recorded in March and August table 3 and the hydrological alteration are approaching the threshold values of RVA, which defines the hydrological alteration as moderate. However, the classification of low and moderate alterations suggests that the changes observed fall within an expected or acceptable range based on historical variability. The comparison of statistical indicators hydrological alteration by module provides valuable insights into the temporal variability of different hydrological parameters [13, 14]. The fact that maximum flow exhibits larger variations can be of particular interest, as extreme flow events can have significant ecological and infrastructure implications [15,16]. Further research will confidently compare the design values of RNPP water intake before and during operation. This will assess the impact and identify natural and man-made factors that may influence any alterations. It is important to acknowledge the potential complexity of this task to ensure all factors are considered.

5. Conclusions

To determine the ecological status of surface water bodies, hydrological indicators should be taken into account, as industrial objects that consume water can change the hydrological and temperature regimes. The Styr River water flow has a seasonal variation. It is thus established that an increase in RNPP water use occurs during the warm season, which is associated with higher temperatures and, consequently, greater evaporation of water in an open recirculating system. In 2019 and 2020, minimum Styr River flows were recorded during the warm season (August, September), these can be identified as periods of low water in the Styr River. Consequently, a positive significant ($p < 0.0001$) correlation was found at level strong ($r = 0.7 - 0.9$) with $R^2 = 0.7623$ between water use and consumption at RNPP and Styr River water temperature; and a positive significant correlation was found at level very strong ($r = 0.9934$) with $R^2 = 0.9869$ between Styr River water temperature before and after discharge. The RVA revealed low hydrological alteration of the Styr River (0-33%) in the RNPP impact zone. Thus, moderate hydrological alterations of the Styr River (33-67%) were recorded once for $G(Q_{dl})$ in 2019 and 2020. In general, the results of the study indicate that the RNPP does not affect the Styr River hydrological alteration, and therefore does not require optimization, as hydrological indicators and their changes do not affect the ecological status of the river and do not impede the achievement of the WFD goals.

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Trends in variability of the distribution of particulate organic carbon in the north-western part of the Black Sea

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Trends in variability of the distribution of particulate organic carbon in the north-western part of the Black Sea

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Abstract. The paper describes the results of a study of the variability in the distribution of particulate organic carbon (POC) concentrations in the north-western part of the Black Sea. The initial data for the calculations were satellite data on the concentration of particulate organic carbon particles. In the process of research, such tasks as the formation of relevant POC databases, built maps of the spatial distribution of POC in the north-western part of the Black Sea in different seasons, the analysis of the intra-annual and inter-annual distribution of POC, and the identification of trends were solved. It was established that the concentration of POC in the north-western part of the Black Sea has a seasonal character with an annual periodicity, with the cyclonic movement of POC along the coast. The maximum concentration of POCs is generally concentrated in wetlands of international importance, indicating that they perform much broader ecosystem functions than filtering and purifying water. These wetlands store blue carbon, occupying a certain link in the marine carbon cycle. This confirms the important role of these coastal ecosystems within the transition of the blue economy of the studied area to sustainable development, namely increasing the contribution to solving climate and biodiversity problems, in accordance with the SDGs: Goal 13 - Climate action, Goal 14 - Life below water, Goal 15 - Life on land. Insufficient consideration of this role in the relevant decisions, in particular according to the Ramsar Convention on Wetlands, will lead not only to a decrease in biodiversity, but also to a deterioration of the climate within the territory of the Northern Black Sea.

1. Introduction

The development of industry and technology over the past centuries has gradually led to an increase in the level of environmental pollution. Today, the seas and oceans contain almost 40 % of carbon dioxide obtained from the atmosphere. This leads to deregulation and negative consequences for the ocean's natural capital and ecosystem services. Oceans absorb and store emissions and sources of pollution, playing a vital role in regulating the global carbon cycle. It is undeniable that the protection and preservation of the ocean environment and biodiversity must be complemented by the goal of reducing emissions and pollution that negatively impact the oceans. This goal fully coincides with the tasks of achieving the goals of sustainable development and blue growth and, accordingly, the sustainability of the blue economy [1–3].

To date, no generally accepted definition of the blue economy has been precisely established. The World Bank defines the blue economy as the sustainable use of ocean resources for economic growth, improving living conditions and jobs while preserving the health of the ocean ecosystem [4]. According to the definition of the European Commission, the blue economy is all economic activity related to oceans, seas and coasts. The blue economy covers a wide range of interconnected existing and emerging sectors [5]. Also, the European Commission defined the working title of a sustainable blue economy – a sustainable blue economy promotes economic growth, social integration and improved livelihoods, while ensuring the environmental sustainability of the natural capital of the oceans and seas. The blue economy encompasses all sectoral and cross-sectoral economic activities related to oceans, seas and coasts. It includes new sectors and economic value based on natural capital and non-market goods and services through the conservation of marine habitats and ecosystem services [6]. Also, according to the definition of the EU [6], the natural capital of the ocean is the stock of natural assets of the ocean with its biotic and abiotic components and services. That is, the natural capital of the ocean provides ecosystem services, which according to the Common International Classification of Ecosystem Services (CICES) can be divided into provisioning services (food, water, energy), regulating services (climate and weather regulation) and cultural services (e.g. recreational benefits). These ecosystem services are the basis for the activity of the blue economy and the associated socio-economic development of the region. The authors [6] note that the ocean's natural capital and associated services are fragile to (cumulative) pressure from human activities. Coastal ecosystems are among the most productive on Earth. They provide essential ecosystem services such as coastal protection from storms and fish feeding grounds. They are also known to provide another essential service – the sequestration and preservation of Blue Carbon from the atmosphere and oceans and are therefore an important part of solving the problem of global climate change [7].

In the natural global carbon cycle, a dynamic equilibrium exists in the global carbon cycle between the surface ocean, the terrestrial biosphere, and the atmosphere. This balance is disrupted not only by fossil-fuel emissions, but also by direct human disturbance of land use and indirect climate warming of the biosphere, especially the permafrost, soils, and the ocean. The global carbon cycle consists of four main subcomponents, or carbon pools, such as: the atmosphere; oceans; terrestrial biosphere (which usually includes freshwater ecosystems and non-living organic material such as carbon in soil), sediments (ocean sediments, plus carbonaceous rocks and fossil fuels) [8]. In marine ecosystems, carbon occurs widely in the form of dissolved organic carbon (DOC), solid organic carbon (POC), dissolved inorganic carbon (DIC), and solid inorganic carbon (PIC). In the active layer of the ocean, DIC, together with nutrients, can be used to produce POC through phytoplankton photosynthesis [9]. Oceans and seas, especially their open areas, because of their vast water areas, are the most important sinks of atmospheric carbon dioxide (CO_2). The high productivity phytoplankton biomass and water carbonate chemistry result in significant uptake of CO_2, the products of which are precipitated into the oceanic carbon sink [8]. Carbon-containing compounds such as Blue Carbon are valuable on Earth. The blue economy is developing due to the huge demand for the synthesis of materials and their application in various fields, such as the food industry, medicine, cosmetology, etc. Blue Carbon obtained from ocean resources also contributes to socio-economic development, which is a reflection of the non-living resource sector components of the blue economy. Blue Carbon refers to organic carbon derived from ocean flora such as seagrass, seaweed, mangroves, and marshes (seaside grasslands). Marine resources derived from carbon sequestration and storage help to boost the economy. Seaweeds are macroscopic and adapted to different conditions of the marine environment. Algae (marine), which are formed by carbon sequestration and the accumulation of many products, are considered a Blue Carbon generator for the development of the blue economy [10].

The dynamics of the particulate organic carbon (POC) pool in the ocean is central to the marine carbon cycle. POC is the link between surface primary production, the deep ocean, and sediments. It is known that the rate of POC decomposition in the dark ocean can influence atmospheric CO_2 concentrations [11]. POC are related to the content of organic carbon in suspended matter, which includes various autotrophic and heterotrophic organisms (phytoplankton, bacteria, zooplankton), as well as organic detrital (inanimate) particles. Compared to the dissolved carbon pools in the ocean, standing stocks of POC are relatively small, but they are important to the marine food chain. These POC stocks are also responsible for relatively large carbon fluxes, including the export of carbon from the surface to the deep ocean via sinking particles as part of a "biological pump" that provides a mechanism for carbon sequestration in the deep ocean and sediments [12].

Determining trends in the variability of the distribution of particulate organic carbon concentrations in the north-western part of the Black Sea was the aim of the research.

2. Related work

Scientists around the world have been conducting research related to climate change for many decades. European standards, based on economic, ecological and social components and aimed at limiting harmful emissions into the environment and its pollution, are introduced into international legal documents. This, in turn, contributes to climate mitigation.

The International Union for Conservation of Nature (IUCN) together with Conservation International (CI) has prepared recommendations for the coordination of actions within the framework of international political processes for the conservation and restoration of coastal blue carbon ecosystems [13] and their implementation in the United Nations Framework Convention on Climate Change (UNFCCC) [14], the Convention on biological diversity (CBD) [15], the Ramsar Convention on Wetlands of International Importance (Ramsar Convention) [16], as well as the Sustainable Development Goals (SDGs) [1]. It is known [7] that according to the definition of Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature: Blue Carbon is carbon stored in coastal and marine ecosystems. Created by these organizations, the Blue Carbon Initiative now focuses on carbon in coastal ecosystems – mangroves, wetlands and seaweed. These ecosystems sequester and store large amounts of Blue Carbon in both the plants and the sediment below.

The international carbon market began to develop in the second half of the last century. As a result, carbon prices are set, carbon credits are introduced, carbon trading and carbon taxation are introduced, penalties for emissions committed without a certain quota (cap and trade), etc [17, 18].

Ecosystems that contain Blue Carbon are disappearing so quickly that they have begun to be classified as one of the most vulnerable ecosystems on Earth. This problem is not ignored. Measures to restore and protect these ecosystems are increasingly being developed. They are mainly based on the same three component dimensions of benefit that support the blue economy, namely: economic, social and environmental. The benefit is an increase in carbon sequestration, as well as an opportunity to significantly reduce the negative impact of factors that destroy ecosystems and, as a result, benefits are also provided for the society that depends on these ecosystems. Blue Carbon recovery and protection measures also open up the potential to develop market-based mechanisms that leverage existing carbon offset mechanisms (known as carbon credits) [19]. The development of reliable and accurate non-market estimates is also accelerating as a result of improved understanding of carbon stocks and flows. These financial incentives for Blue Carbon can also help protect and benefit from other ecosystem services provided by these ecosystems, such as healthy fisheries, improved water quality, and coastal protection from floods and storms. This, in turn, will bring additional benefits beyond the direct benefits of carbon sequestration. The authors [19] claim that Blue Carbon meets all three main elements of sustainable development – economic, environmental and social. Based on this, Blue Carbon should be considered as the most important component of the blue economy.

Together with the renewable energy sector and the carbon sequestration and storage industries, Blue Carbon is emerging as an industry in its own right, helping the global transition to a "low carbon" economy. This, in turn, contributes to the creation of economic opportunities, which are very important for both developing countries and developed countries or developed industries.

The European Commission has developed criteria and indicators for assessing the sustainability of the blue economy [6]. They are based on four dimensions of sustainability: environmental, economic, social and governance. According to the European Commission, the subsector "Storage of CO_2/Carbon sequestration" of the blue economy sector "Non-Living Resources" is an actively developing subsector today. Therefore, a consolidated list of relevant criteria and indicators for this subsector has not been fully formed. Today, the EU proposes to focus on the following areas of the components of sustainability measurements in this specific subsector [6]:

- Carbon dynamics (e.g. carbon burial rate; change in the amount of carbon gained or lost over time; amount of carbon stored per unit area (carbon density) are used to describe the carbon sequestration / Blue Carbon sector – Environmental);
- Carbon valuation (e.g. the economic value of blue carbon ecosystems per hectare (Ecosystem service value per hectare (US$); carbon price – Economic / Governance);
- Climate change (mitigation – Governance).

3. Materials and methods

Global observations of ocean color from space have been ongoing since the late 1990s and will continue for the foreseeable future thanks to a multitude of satellite missions. This observational approach provides a unique opportunity to monitor long-term trends in satellite data products characterizing biogeochemical components and processes in the upper ocean at regional, basin, and global scales. One such data product of significant interest for the study of ocean carbon cycles is the concentration of particulate organic carbon (POC) in surface ocean waters [12]. Today, despite many researches the identification and analysis of trends and anomalies in the long-term variability of characteristics in the marine environment are under the major focus [20].

The research process was based on the following stages:

1. Formation of POC databases
2. Build of POC spatial distribution maps.
3. Analysis of the variability of the spatial distribution of POCs by season between 2000 and 2023 and their overall distribution over the entire period.
4. Identifying trends.

The initial information for the research was satellite data of particulate organic carbon (POC) in the period from 2000 to 2023 [21]. These data were measured by NASA's Tera (MODIS) satellite. Processing of raw data was carried out using MatLab software. Verification of POC satellite data processing was performed using specialized NASA software – SeaDAS. SeaDAS (SeaWiFS Data Analysis System) is a comprehensive software package for processing, displaying, analyzing and quality control of Earth remote sensing data. NASA is the official distributor of SeaDAS science software [22]. Maps of the spatial distribution of POC in the north-western part of the Black Sea were built using ODV (Ocean Data View) software. The ODV software is designed for interactive exploration and graphical display of oceanographic profiles, trajectories or time series data [23].

The statistical characteristic (β_{poc}) characterizing the variability of POC concentration per year was calculated using a well-known equation [24, 25]:

$$\beta_{poc} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2} \quad (1)$$

where y_i – the value of POC concentration in a long-terms series of observations, x_i – a unit of time in a long-term series of observations, n – the number of members of long-terms series.

Identification of trends in POC variability was carried out on the basis of graphical material built using averaged satellite data in the period 2000–2023.

4. Results and discussion

Studies of POC variability have been concentrated in the north-western part of the Black Sea. After all, it is known that in this part of the Black Sea there are ecosystems that with a high probably contain blue carbon – this is the world's largest colony of red algae – the Zernov's Phyllophora Field, the condition of which has improved from "poor" to "moderate" according to the results of a joint EU and UNDP project [26]. There are also 7 wetlands of international importance along the coast, namely: Kyliiske Mouth, Sasyk Lake, Shagany-Alibei-Burnas Lakes System, Dnipro River Delta, Yagorlytska Bay, Tendrivska Bay, Karkinitska and Dzharylgatska Bays [27]. In addition, on the basis of the UN Convention on the Law of the Sea [28], which was ratified by the legislation of Ukraine in 1999 [29], the shallow northwestern part of the Black Sea includes the territorial waters, contiguous zone and exclusive economic zone of Ukraine. According to Article 4 of the Law of Ukraine "On Exclusive (Maritime) Economic Zone of Ukraine" [30]: "In its exclusive (maritime) economic zone, Ukraine has sovereign rights to explore, exploit and conserve natural resources, both living and mineral, in the waters covering the seabed, at the seabed and under seabed, as well as rights to manage these resources and rights to conduct other activities of economic exploration and development of the said zone, including the production of energy by means of using of water, currents and wind".

4.1. Formation of POC concentration databases for conducting research in the north-western part of the Black Sea

Satellite observation data from 2000 to 2023 were used to build maps of the spatial distribution of POC concentration by season and in general for the entire period. The number of averaged data for the studied period was about 9500 measurements for the seasonal distribution of POC, and about 2400 measurements for determining the spatial distribution of POC in general for the entire period.

To analyze the intra-annual distribution of POC concentration, a database of average monthly values for the period from 2000 to 2023 was formed. The number of averaged data was about 28000 measurements.

A database of average annual values for the period from 2000 to 2022 was created to identify trends in the POC concentration distribution. The number of these data was about 54500 measurements.

4.2. Analysis of the variability of the spatial distribution of POC concentration in the north-western part of the Black Sea

Maps of POC distribution in different seasons were built to analyze the variability of the spatial distribution of POC concentrations in the north-western part of the Black Sea. Averaged POC data for the period 2000 – 2023, which were formed into the appropriate database, served as initial data for building maps. Built maps are shown in figure 1.

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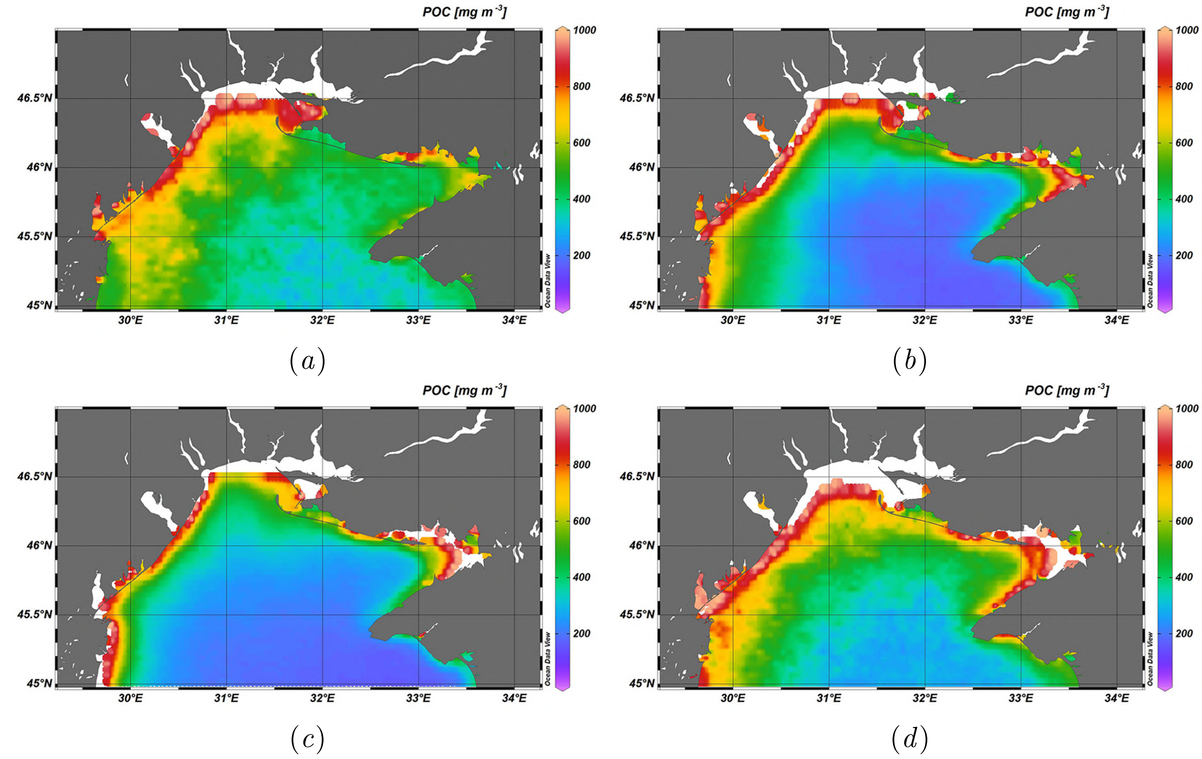

Figure 1. Maps of the spatial distribution of POC concentration in the north-western part of the Black Sea by seasons: (a) – winter, (b) – spring, (c) – summer, (d) – autumn.

In figure 1 (a), the maximum concentration of POC is observed along the coast from the Yagorlytska Bay to the Kyliiske Mouth, as well as in the area of the Dzharylgatska Bay. From these areas with the maximum concentration of POC, its decrease spreads to the south of the north-western part of the Black Sea.

In spring (figure 1 (b)), the maximum concentration of POC along the coast increases in the southern direction and reaches the end of the Danube Delta. In the east of the north-western part of the Black Sea, an increase in the concentration of POC is also observed along the coast in the southern direction from the Dzharylgatska Bay to almost the entire water area of the Karkinitska Bay. The minimum concentration of POC is observed in the central, southern and eastern (region of the western part of Crimea) parts of the studied area of the sea.

In summer (figure 1 (c)), in general, the POC concentration decreases in the water area of the north-western part of the Black Sea. Areas with maximum POC concentration remained the same as in spring except for the northern part of the study area. A decrease in POC concentration is observed in this area. In contrast to figure 1 (b), the minimum values of POC concentration extend to the west of the central part of the studied area.

Figure 1 (d) shows that in autumn there is a clear increase in the concentration of POC throughout the water area of the north-western part of the Black Sea. Small areas with minimal POC concentration are observed in the southern part of the water area of the studied area.

To visualize the general spatial distribution of POC concentration in the north-western part of the Black Sea in the period from 2000 to 2023, a corresponding map was built (figure 2).

Figure 2 shows that the maximum concentration of POC extends behind the cyclonic movement along the coast from the Yagorlytska Bay and the Tendrivska Bay to the Danube Delta, as well as in the water area of the Karkinitska and Dzharylgatska bays. The minimum concentration of POC is observed in the central, southern and eastern (region of the western

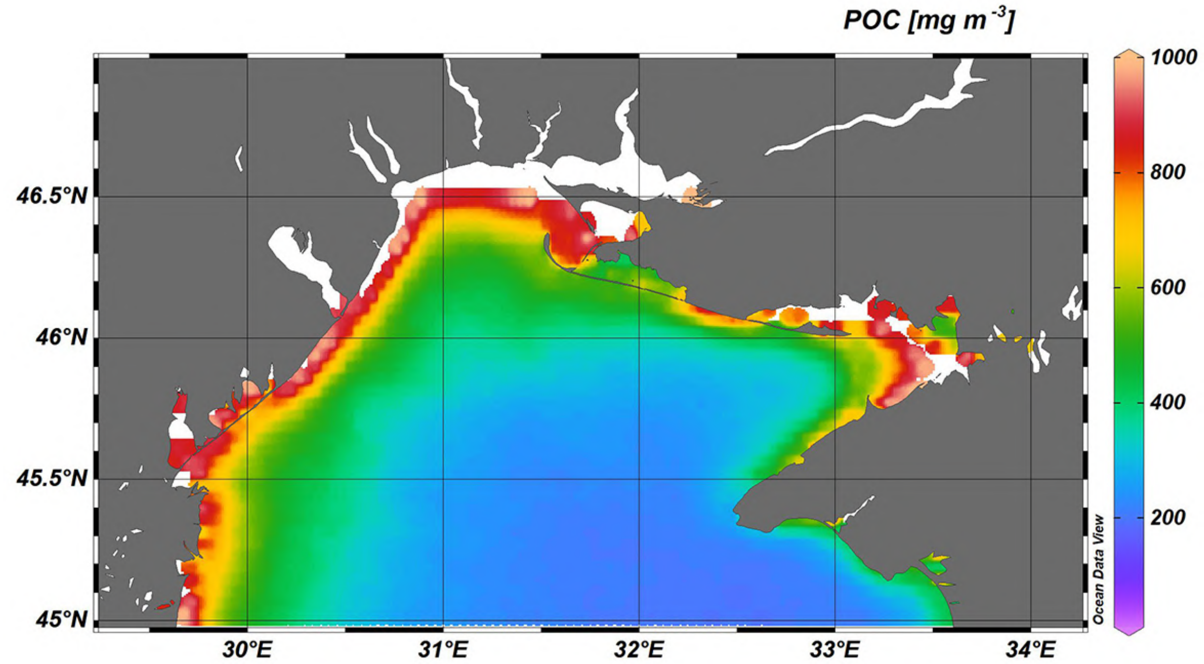

Figure 2. Map of the spatial distribution of POC concentration in the north-western part of the Black Sea as a whole for the period from 2000 to 2023.

part of Crimea) parts of the studied area of the sea.

Thus, based on the maps built (figure 1 and figure 2), we can conclude that the maximum concentration of POC in the north-western part of the Black Sea is generally concentrated in the areas of wetlands of international importance. Its movement has a cyclonic character along the coast and is caused by the general circulation of waters in this area. The width of the maximum POC concentration band depends on the season. The minimum width is observed in summer and increases until winter.

4.3. Identification of POC concentration distribution trends in the north-western part of the Black Sea

To analyze the intra-annual distribution of POC concentration in the north-western part of the Black Sea, a corresponding graph was built (figure 3). The initial data were satellite data of POC concentrations averaged for each month in the period 2000–2023.

From figure 3 it can be seen that the maximum concentration of POC is observed in December/January and is about 647 mg/m^3. The minimum concentration of POC occurs in July and is about 327 mg/m^3. In general, the annual periodicity can be observed in figure 3.

To identify trends in the distribution of POC concentration in the north-western part of the Black Sea, a graph of its interannual variability was built (figure 4). Satellite data of POC concentration averaged for each year in the period 2000-2022 served as initial data.

Figure 4 shows the maximum interannual variability of POC concentration in 2000, 2004-2005, 2007, 2009 and 2017. Clear minimums can be singled out in 2003, 2008, 2014 and 2018. Overall, figure 4 illustrates to us a clear downward trend in the time series of POC concentration variability with an absolute maximum in 2000 of about 518 mg/m^3 and an absolute minimum in 2014 of about 344 mg/m^3. In the fifteen years from 2000 to 2014, the POC concentration in the north-western part of the Black Sea decreased by 1.5 times. In 2022, the concentration of POC

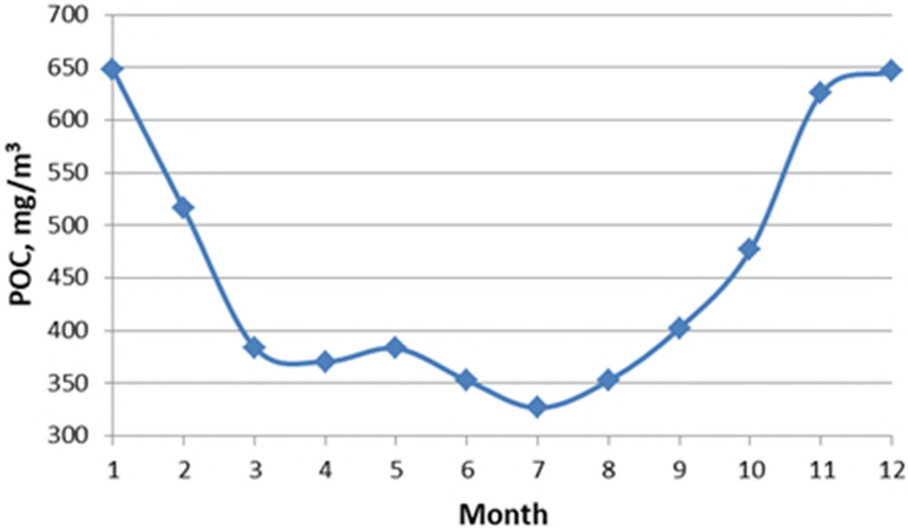

Figure 3. Graph of intra-annual distribution of POC concentrations in the north-western part of the Black Sea based on average monthly data in the period from 2000 to 2023.

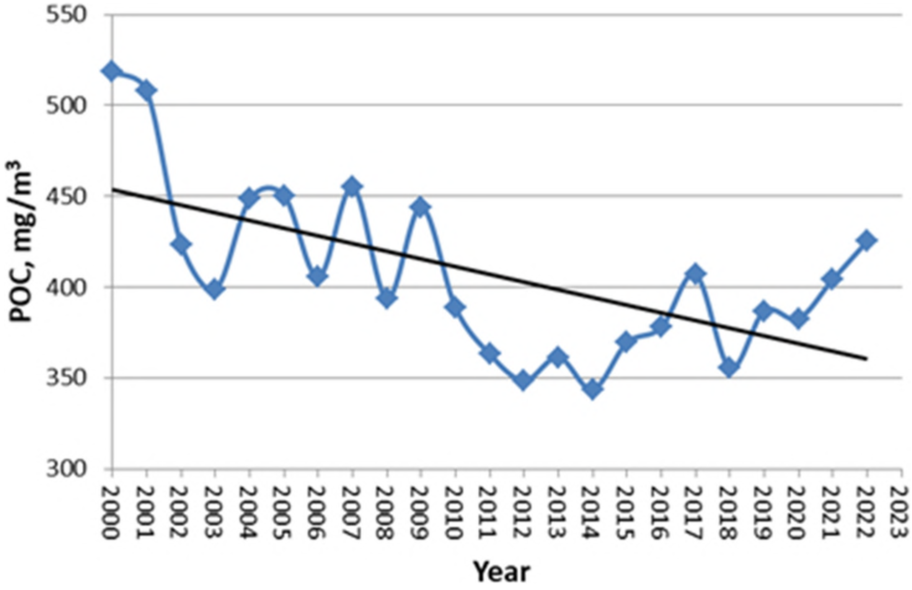

Figure 4. Graph of interannual variability of POC concentration in the north-western part of the Black Sea based on data averaged for each year in the period from 2000 to 2022.

was already about 425 mg/m^3, which increased almost 1.2 times compared to the indicators of 2014.

Statistical assessment of the variability of the downward trend of POC concentration per year (β_{poc}), which was calculated according to the well-known equation (1), was β_{poc} = -4.22 mg/m^3 per year. This indicator shows that over a total of 23 years, the concentration of POC in the surface layer of the north-western part of the Black Sea decreased by 4.22 mg/m^{-3} per year. Based on the result of the β_{poc} indicator, it can be stated that the amount of POC in the surface one-meter layer of the north-western part of the Black Sea decreases by approximately 200 tons per year.

5. Conclusions

Based on the obtained calculation results, it can be asserted that the variability of the concentration of POC in the north-western part of the Black Sea has a seasonal character with an annual periodicity, with the cyclonic movement of POC along the coast. The maximum concentration of POCs is generally concentrated in wetlands of international importance, indicating that they perform much broader ecosystem functions than filtering and purifying water. These wetlands store blue carbon, occupying a certain link in the marine carbon cycle. This confirms the important role of these coastal ecosystems within the transition of the blue economy of the studied area to sustainable development, namely increasing the contribution to solving climate and biodiversity problems, in accordance with the SDGs: Goal 13 – Climate action, Goal 14 – Life below water, Goal 15 – Life on land. Insufficient consideration of this role in the relevant decisions, in particular according to the Ramsar Convention on Wetlands, will lead not only to a decrease in biodiversity, but also to a deterioration of the climate within the territory of the Northern Black Sea. Considering the fact that a large part of these territories has suffered damage as a result of military operations and / or is under Russian occupation, the situation is very difficult.

The task in the wartime is to preserve the health of the studied ecosystems as much as possible, with the involvement of specialists and observers of regional and national, as well as international levels. The post-war period will require the restoration of wetlands, as well as the development of a national blue carbon strategy within the coastal ecosystems of Ukraine. This strategy will provide for a range of nature-based solutions within the scope of area expansion and regeneration of wetlands of international and national importance. The basis of financing the implementation of this strategy should be state regional support with the addition of international financial instruments, primarily through Ukraine joining the World Bank's Blue Economy Program (PROBLUE) and other international environmental programs. This will allow the country to systematically receive targeted financial assistance and become a full participant in the blue bond market. It is also expected to expand the range of ecosystem services of wetlands, in particular recreational fishing and ecological tourism, thereby increasing the contribution to the sustainability of other sectors of the blue economy.

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Analysis of current trends in water runoff of the Sluch River in terms of extraterritorial impacts of hydrotechnical construction

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Analysis of current trends in water runoff of the Sluch River in terms of extraterritorial impacts of hydrotechnical construction

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Abstract. The aim of the conducted research was to uncover current trends in the variability of the Sluch River's flow in the context of potential depletion of its water resources due to climate change and anthropogenic activity in its catchment area. The research methodology relied on the analysis of time series data from hydrological observations of average annual, maximum, and minimum water flows. Modern trends in the variability of the river flow were determined using data collected from three operational hydrological posts located at different sections of its course: "Hromada" in the upper part of the river basin, "Zviahel" within the middle course, and "Sarny" in the lower course. The total monitoring period for establishing modern trends in the variability of the river flow spanned 27 years, from 1989 to 2015. The research revealed that the minimum flow of the river underwent the most significant negative changes in the context of water resource depletion during this period. This finding was particularly evident at the Zviahel hydrological station.

1. Introduction

According to the well-known forecast by Rodda [1], made by him at the end of the last century, by 2035-2045, the consumption of fresh water in the world may equal its available stored resources. The UN report "Water Resource Management in Conditions of Uncertainty and Risk" [2] on the state of global freshwater resources noted that in case of unfavorable circumstances, already within the 21st century, 7 billion people on Earth from 60 countries will face a real problem of drinking water shortage; under favorable conditions, this problem will still exist in 48 countries worldwide, where 2 billion people reside. The final conclusion is disheartening: if the situation does not change, by 2030, the global water resource deficit on the planet will reach 40% [3].

It is expected that over time, the water resource deficit, particularly in the context of river runoff resources, which is the main source of drinking and industrial water supply in most countries worldwide, will only intensify [4,5]. This is already a global water management problem, which, despite the efforts of the global community, becomes more acute with each passing year, and for several countries worldwide, the deficit of water resources poses a threat to their very existence. Its essence lies not only in the fact that the water resource potential of humanity for ensuring river runoff is quantitatively limited, but also in the highly uneven geography of its distribution globally, which is significantly inversely proportional to the needs of the main consumers of freshwater – the population and participants in economic activities [6].

The fact that water resources can become one of the limiting factors for socio-economic development, both for Ukraine as individual sectors of its economy and entire regions, was noted by scientists [7] as far back as the 1970s. However, despite the large-scale hydrotechnical construction within the country in the 1950s-1980s, involving the creation of large reservoirs on the Dnieper, Dnister, Southern Buh, and other rivers capable of accumulating significant water volumes and redistributing them throughout the year according to needs, as well as numerous calls from scientists for the rational use and protection of water resources, especially river runoff resources, the issue of depletion and deficit of water resources in the country has not only remained relevant but continues to intensify over time [8, 9].

Among the main issues of water use in Ukraine, the following are prominent: a general deficit of water resources in the country, uneven territorial distribution, and peculiarities of international integration (not in favour of Ukraine). Alongside this, there is a high water demand in the domestic economy, irrational use, and excessive pollution of water resources, leading to the unsatisfactory state of exploited water bodies [9].

Indeed, in terms of internal reserves of freshwater per capita, Ukraine ranks 111th globally out of 152 countries and territories (according to World Bank statistics) [9] and is one of the least water-supplied countries in Europe. The reserves of local resources of river flow in Ukraine amount to about 1.0 thousand m^3 per year per person. For comparison, in European countries, this indicator is as follows: Norway – 96.9 thousand m^3 per year; Sweden – 24.1; Finland – 22.5; France – 4.6; Italy – 3.9; Great Britain – 2.7; Poland – 1.7; Germany – 1.3 thousand m^3 per year [10]. While the western regions of the country are the most endowed with river runoff resources, ranging from 2 to 7 thousand m^3 per year per inhabitant, the least endowed with surface water resources are the most industrially developed southeastern regions: Kherson, Donetsk, Dnipropetrovsk, Zaporizhia, Luhansk – from 0.1 to 0.5 thousand m^3 of water per year. At the same time, only 25% of the volume of potential river flow resources of Ukraine is formed within its territory; the rest comes from the Russian Federation, Belarus, Poland, Hungary, Moldova, and Romania [10, 11].

Extensive anthropogenic transformation of landscapes within river basins due to agricultural production in watersheds, excessive involvement of river waters in economic circulation, their pollution, and irreversible losses (up to 12% of water intake [10]), and, simultaneously, a high level of river flow regulation thanks to hydrotechnical construction and hydromelioration – all these significantly disturbed the natural balance of most river ecosystems, changed the hydrological regime of rivers, and led to the depletion of water resources in many regions of Ukraine [8]. All these phenomena also take place in the basin of the Sluch River, one of the important rivers for the economy of three regions, the flow of which is completely formed within the borders of Ukraine. This makes it possible to analyse modern trends in changes in its flow regardless of cross-border anthropogenic influences.

Climate changes, which have intensified since the middle of the last century, have impacted the water regime of rivers, including those flowing within the territory of Ukraine. Alongside climatic changes, significant contributions to alterations in river discharge have been made by anthropogenic pressures on their watersheds [11–14].

According to the results of recent studies by Ukrainian hydrologists, the onset of the period of modern changes in the hydrological regime of rivers in Ukraine, including those in the Pripyat River basin, can be traced back to 1989 [11–14]. For convenience, this year has been chosen as a reference point for analyzing the contemporary trends in the variability of the Sluch River's

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runoff.

2. Description of the research area

The objective of the study was to identify current patterns in the fluctuation of the Sluch River's flow, considering the potential depletion of its water reserves attributed to both climate change and human activities within its watershed. The main tasks include analyzing general flow trends separately for warm and cold periods, processing maximum and minimum annual runoff. Additionally, for a clearer understanding of the factors influencing flow conditions, we present and analyze a geoinformation model of the catchment area.

The Sluch River belongs to the Dnieper River basin, it is the right and largest tributary of the Horyn River. Originating from a small lake in the Podolian Upland near the village of Chervony Sluch in the Teofipol district of the Khmelnytskyi region of Ukraine, it flows through three regions: Khmelnytskyi, Zhytomyr, and Rivne.

The total length of the Sluch River is 451 km, ranking as the 18th longest river in Ukraine. In terms of the watershed area (13.8 thousand km^2), it occupies a position in the third decade. However, the Sluch is the longest fourth-order river in Ukraine (its waters initially flow into the Horyn River and then into the Pripyat River before reaching the Dnieper). Its primary source of nourishment is mainly snowmelt and rainfall.

The width of the river valley ranges from 0.2-0.8 km in the upper reaches to 5 km in the lower reaches, where it traverses the Polissya Lowland. The riverbed varies from 5 to 50 m, with the maximum width reaching 110 m. The average gradient of the river is 0.4 m/km. Within the Volyn-Podolian Plateau, from the town of Starokostiantyniv (Khmelnytskyi region) to the town of Sosnove (Rivne region), the river flows through an area of crystalline massif. Here, it runs through crystalline rocks (granites, gneisses) with rocky banks and numerous rapids. The river freezes in December and thaws in March.

The Sluch River receives the inflow of 1643 small rivers with a total length of 6136 km. Major tributaries include Ikopot, Derevichka, Khomora, Smilka, Tserem, Korchyk, Stavy, Serehivka, Yazvinka (left); Tnia, Tyukelivka, Popivka, Bober (right).

Several towns and significant settlements, such as Baranivka, Zviahel, Kuzmin, Voronkivtsi, Starokostiantyniv, Hromada, Liubar, Polonne, Myropil, Rohachiv, Chyzhivka, Horodnytsia, Korets, Sosnove, Berezne, Sarny, and numerous villages, are situated along the banks of the Sluch River and its tributaries. The river basin is home to more than 200 ponds and 17 reservoirs, including 39 directly on the Sluch River.

Partially, the water resources of the river and its tributaries are utilized for water supply. In particular, the Zviahel Reservoir on the Sluch River serves as the sole source of municipal and industrial water supply for the city of Zviahel, for which there is currently no alternative. Additionally, six mini hydroelectric power stations (MHPS) operate on the river: Myropilska (with a capacity of 500 kW) and Pedynkivska (600 kW), which have been in operation for more than 50 years since 1957 and 1959, respectively; Korzhivska (320 kW), built in 1953 and restored in 2004; Liubarska (200 kW), constructed in 1950 and restored in 2006; Chyzhivska (600 kW), built in 1951 and restored in 2015; and Baranivska (382 kW), constructed in 2017.

Artificial water bodies (reservoirs, ponds) are important infrastructure objects in the economy of Ukraine and many other countries [15]. Alongside performing vital water management functions (municipal and technical water supply, irrigation, hydroelectric power,fish farming, flow regulation, flood control, recreation, etc.), they significantly alter river flow [16], including the minimum flow. And these changes, including those concerning minimum flow, are not always positive, including, as practice shows, for certain participants and objects of the water management complex [17, 18], which provide for the livelihoods of the population or perform functions critical to the functioning of the national economy and, accordingly, may be considered as critical infrastructure objects.

Jurik et al. [17] categorize reservoirs into three distinct groups, identify hydromelioration structures, watercourses and substantial water reserves, health and water management structures, which play a vital role in managing water resources within municipalities, towns, and industrial facilities. All of that types presented within Slych River basin, including reservoirs for water supply and small hydropower, numerous ponds and reservoirs. The Kuzminsky Pond in the upper reaches of the river (village of Kuzmin, Krasylivskyi district, Khmelnytskyi region), with its first documented mention dating back to 1480, and the Nemovytske Reservoir downstream (Rivne region), are also renowned ornithological reserves. All of this results in significant anthropogenic pressure on the river. Currently, there is no small river or stream in the Sluch River basin that remains untouched by human activity.

The state of the water resources of the Sluch River is significantly influenced by the negative impacts it undergoes during water use and economic activities within its basin. The primary pollutants entering the river come from discharges of wastewater from residential and municipal areas (Lyubarsky, Baranivsky, Novohrad-Volynsky, Sarnensky), as well as discharges from the Myropil and Mokva paper mills, the Horodnytske porcelain factory, and others. Agriculture, which is also one of the sources of persistent water pollution, is the main land user in the Sluch River basin. In recent years, the largest left tributary of the Sluch, the Khomora River, has been particularly affected by pollution from discharges of the Poninky paper and cardboard factory. The anthropogenic impact on the Sluch is increasing annually, partly due to recreational activities and increased water consumption.

Throughout its length, the river has undergone significant hydro-morphological changes, especially evident in the lower reaches (figure 1), which may be associated with the regulation of flow and the operation of numerous hydrotechnical structures in its basin.

Despite clear signs of degradation based on hydrobiological, hydrochemical, and hydromorphological indicators, the ecological status of the Sluch River, according to basin principles, is still classified by domestic scientists as 'satisfactory'. However, there is a risk that the hydro-morphological and hydrobiological changes that have occurred are already so profound and extensive that, according to international standards, the Sluch River may be categorized as a waterbody significantly altered. The assessment of the structure of individual watersheds was carried out using Landsat data, and the results are presented in table 1.

Table 1. Primary types of land in the context of separate catchments.

Main types of land and land use	Hromada	Hromada-Zviahel	Zviahel-Sarny
total area, km^2	2480	4982	3358
including:			
1. Agricultural land	2313.7 93%	3918.7 79%	1306.1 39%
2. Forests and other forested areas, marshy lands	137.7 6%	887.6 18%	2029.5 60%
3. Built-up lands, surfaces of water bodies	19.2 1%	22.4 0.45%	7.2 0.2%
5. Bare lands without vegetation cover or with minimal vegetation cover	9.4 0.4%	153.3 3%	15.2 0.5%

(a)

(b)

Figure 1. River Sluch in the summer of 2018: a) overgrowth of the riverbed with aquatic vegetation near the village of Bilchaky; b) sedimentation in the riverbed near the village of Marynyn.

3. Results and discussion

In figure 2, a geoinformational hydrological model of the Sluch River watershed is presented, highlighting the catchment areas that contribute to the discharge at the three operational hydrological stations along the river: "Hromada" – in the upper part of the river basin; "Zviahel" – in its middle course; "Sarny" – in the lower course of the river, not far from its confluence with the Horyn River.

The hydrological station "Hromada" (station code 79543) is situated 312 km from the river mouth near the village of Hromada in the Lyubarsky district of the Zhytomyr region, bordering the Khmelnytsky region. The catchment area controlled by this hydrological station, as indicated in the water cadastre, covers 2480 km^2 (approximately 18% of the total catchment area).

The hydrological station "Zviahel" (station code 79545) is located 199 km from the river mouth in the city of Zviahel, in the Zhytomyr region. The catchment area controlled by this hydrological station, as indicated in the water cadastre, encompasses 7460 km^2 (about 54% of the total catchment area).

Hydrological station "Sarny" (station code 79549) is situated near the town of Sarny in the Rivne region. The watershed area controlled by this hydrological station, as indicated in the water cadastre, covers 13,300 km^2 (over 96% of the total watershed area of the Sluch River).

To establish the contemporary trends in the variability of the Sluch River discharge, existing time series data for annual, maximum, and minimum water flows during both 'warm' and 'cold' periods were investigated over the interval from 1989 to 2015. The total duration of the hydrological observations period was 27 years, providing a sufficiently lengthy dataset for relevant trend analysis.

General trends in the change of warm and cold period annual, maximum, and minimum flows were assessed based on exponential trends for uniform comparison across different hydrological stations and different flow periods. The results of trend modeling are presented in figure 3, and their analysis revealed the following.

Overall, from 1989 to 2015, the Sluch River exhibited the smallest changes in annual and maximum flows, while its minimum flows experienced relatively greater changes.

Notably, there are virtually 'zero' trends in annual and maximum flows for the Sluch River from 1989 to 2015 at the hydrological stations "Zviahel" and "Sarny".

Significant differences in trends for different flow periods throughout the year were observed between the hydrological station "Hromada" and the stations "Zviahel" and "Sarny" over the period from 1989 to 2015.

In contrast to the "Zviahel" and "Sarny" stations, the "Hromada" station, during this time interval, shows moderate negative trends (tendencies to decrease) in both annual flows (trend determination coefficient $R^2 = 0.106$) and maximum flows ($R^2 = 0.138$). Simultaneously, despite the practical absence of a trend for the time series of 'warm' period minimum flows at the "Hromada" station, there is a noticeable positive trend (tendency to increase over time) for the corresponding time series of 'cold' period minimum flows ($R^2 = 0.247$). This increase in flows, specifically the 'cold' period minimum flows at the "Hromada" station, represents the only such case among the analyzed hydrological time series (figure 3) characterizing the water flow of the Sluch River based on the available hydrological observations.

At the same time, for the "Zviahel" station, located downstream from "Hromada", pronounced negative trends (tendencies to decrease over time) are already evident for minimum flows during both 'warm' ($R^2 = 0.281$) and 'cold' periods ($R^2 = 0.134$). The least changes in flow characteristics for the designated period are observed at the "Sarny" hydrological station. Here, a negative trend is present only for the 'warm' period minimum flows ($R^2 = 0.18$).

As of today, effective methodologies have been developed for assessing hydro-morphological changes in river channels using remote sensing data [19, 20]. To ensure efficient river basin management [21, 22], traditional and community monitoring should complement satellite

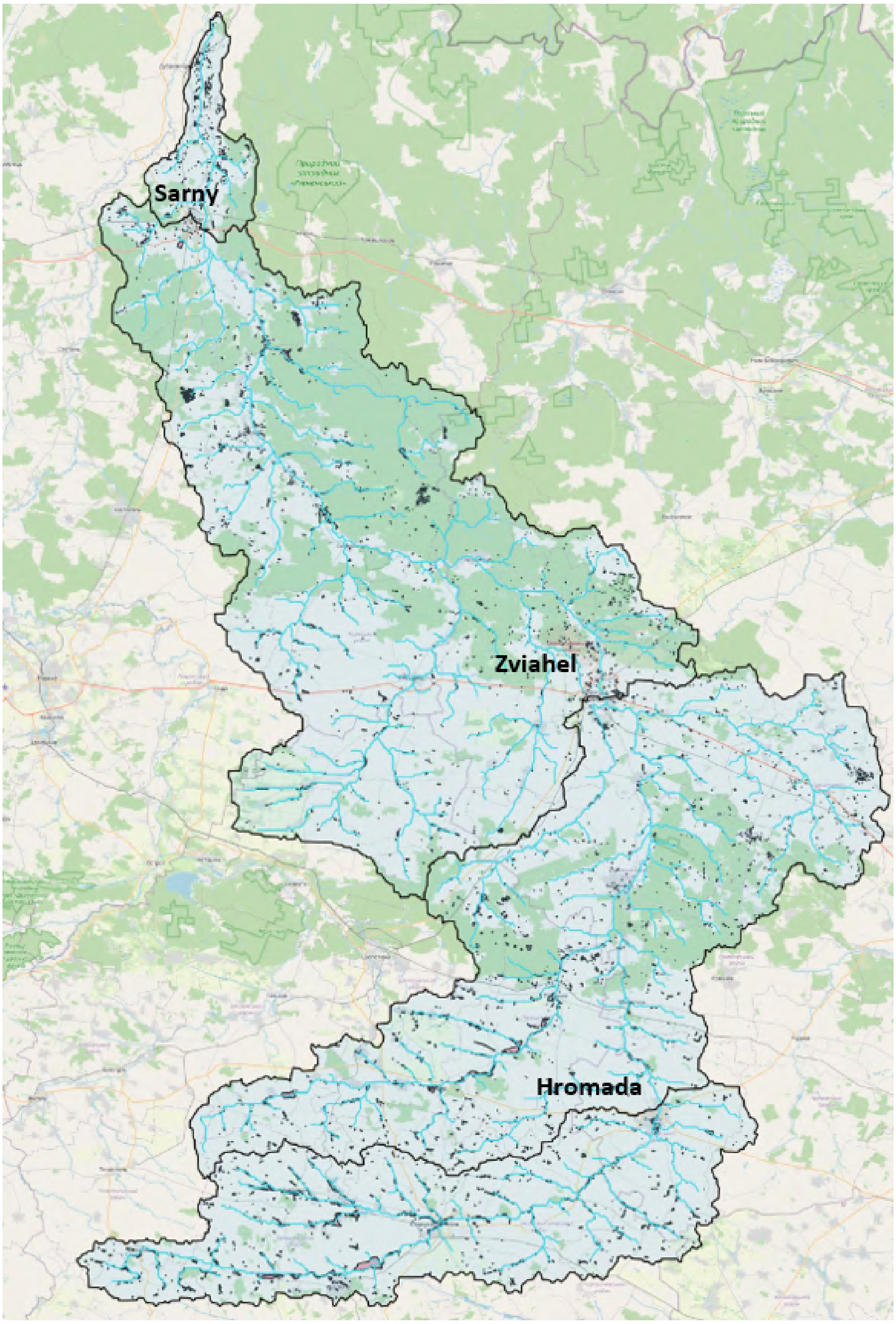

Figure 2. Hydrological model of the Sluch River catchments.

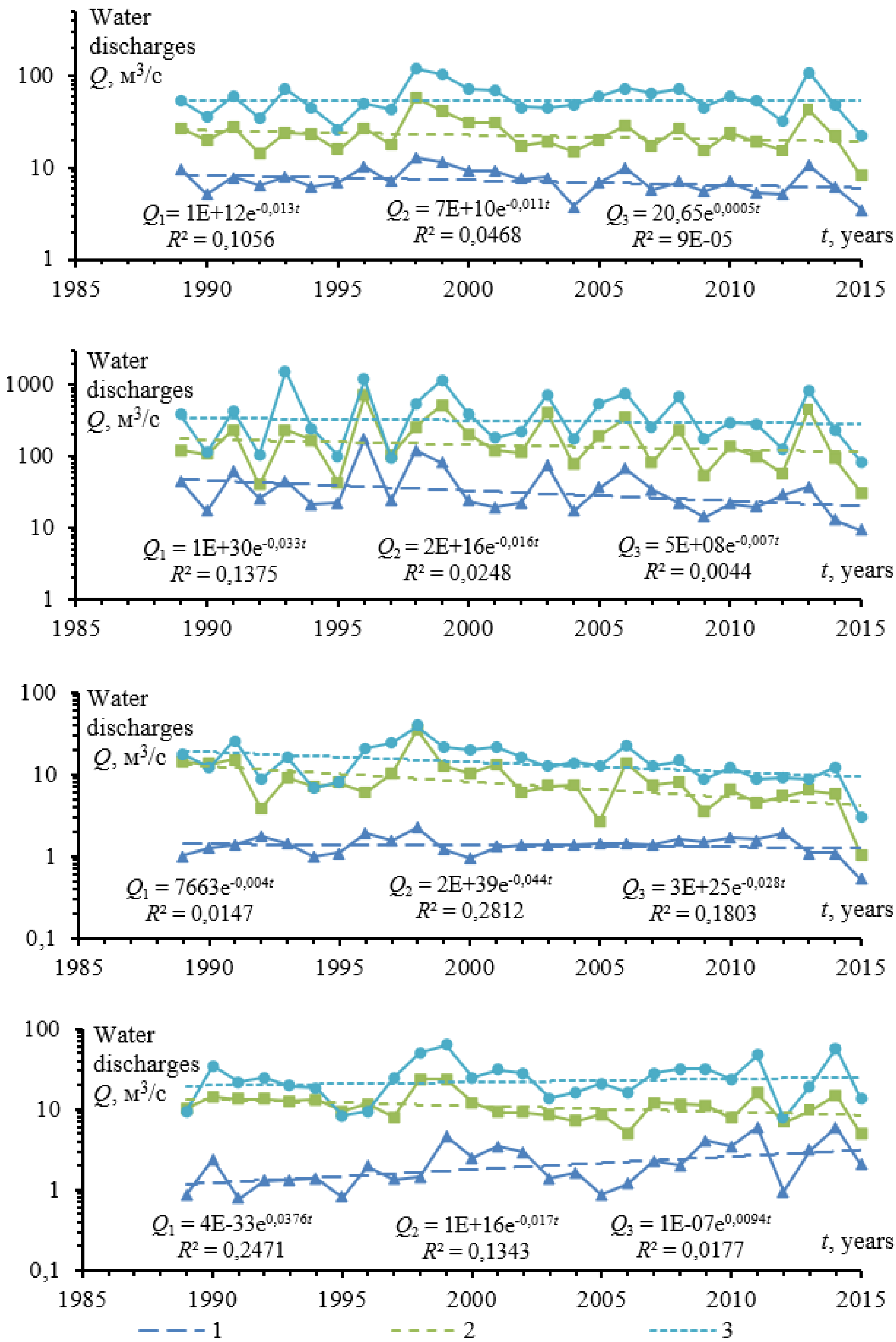

Figure 3. Trends of changes during the period from 1989 to 2015 in the average (a) and maximum (b) water discharges; minimum discharges during the 'warm' period (c), and minimum discharges during the 'cold' period (d) of the Sluch River at the hydrological stations “Hromada” (1), “Zviahel” (2), and “Sarny” (3).

technologies. The synthesis of modern and retrospective data should provide an answer to the genesis of changes in the river system – whether it is the result of climate change or perhaps inexpert decisions regarding land management and construction on the rivers.

4. Conclusions

The contemporary trends of flow variability in the Sluch River have been identified and assessed in the context of the depletion of its water resources due to climate change and anthropogenic activities in the watershed. The assessment was based on time series data of observations on average annual, minimum (for two distinct periods – warm and cold), and maximum water flows, measured at three hydrological stations situated along different sections of the river: "Hromada" – in the upper part of the river basin; "Zviahel" – within the middle course; "Sarny" – in the lower course. The overall duration of the monitoring period for flow rates was 27 years: from 1989 to 2015. It was found that the most significant negative changes in the context of water resource depletion during this period occurred in the minimum flow of the Sluch River at the "Zviahel" hydrological station.

The transformation of the Sluch River's minimum flow has led to its degradation and further deterioration of its condition. The restructuring of the river regime exhibits a certain inertia from the moment the destabilizing factor begins to act. Therefore, without spatial-temporal analysis, it is difficult to ascertain the reasons for changes in water bodies, as the action combines both global and local factors. However, land management can be aimed at reducing water deficits and their impact on the quality of water bodies and the necessary minimum conditions for preserving biodiversity. Among the priority measures may be the development of plans for the use of local runoff with minimal losses, especially during low-water periods, as well as maintaining such flow and velocity regimes in river sections that do not hinder their restoration. To achieve this, it is necessary to abandon the perception of the river solely as an industrial resource intended to address local economic issues. Ultimately, this not only imposes significant economic losses on water users throughout the river basin but also put in risk the functioning of critical infrastructure elements.

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Identification of approaches to developing a response plan for potential emergencies caused by external water contamination

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Abstract. The requirements are analysed and the basic principles of developing a Response Plan for emergencies caused by water contamination are defined. Under martial law, the problem of drinking water safety and quality should be considered from the perspective of a possible threat of enemy use of chemical, biological and radiation-nuclear weapons to damage water management facilities, water supply and sewage systems. Monitoring of water quality at water supply facilities should be carried out on a continuous basis using indicator physical and chemical parameters without the constant presence of personnel. In the event of a sharp change in any of the defined indicators, an operational system for detecting hazardous substances in water should be connected. The paper develops the basic principles of organization, technical, methodological and financial support for water contamination monitoring.

1. Introduction

One of the principles of the state policy of Ukraine in the field of drinking water and drinking water supply is the priority of drinking water supply over other types of special water use and, at the same time, the preventive nature of measures to protect sources and systems of drinking water supply [1].

But the reality is that water resources have been a source of contention and have been weaponized in various political and armed conflicts throughout history. The control and manipulation of water sources can be a strategic tool to exert influence, create vulnerabilities, and achieve political or military objectives. In [2–5] the multifaceted nature of how water resources and related infrastructure can be weaponized in conflicts is emphasized. This involves not only the direct manipulation of water systems for strategic purposes but also the intentional or incidental targeting of these resources and the people associated with them.

Under martial law, when it is obvious that the aggressor is trying to destroy critical infrastructure in Ukraine, it is necessary, in particular, to assess the situation with centralized water supply from the standpoint of a possible threat of the enemy's use of chemical, biological and radiation-nuclear weapons to destroy water sources, water treatment facilities, water networks, other water supply and sewage facilities and deterioration of tap water quality.

The possibility of such actions is confirmed by the explosion of the Kakhovka Hydroelectric power plant (HPP) and the destruction of the Kakhovka reservoir, which negatively affected the water quality of the Dnipro River, in particular in the area of drinking water intakes.

Among the main factors that led to the deterioration of the Dnipro River water quality are the following [6–12]:

- destruction of the Kakhovka reservoir;
- a sudden runoff of more than 10 billion cubic meters of water from the Kakhovka reservoir;
- significant changes in the hydrological regime throughout the Dnipro River catchment area;
- washing downstream of the Dnipro River of the bottom sediments of the Kakhovka Reservoir;
- flooding and possible washout of fuels and lubricants, a wide range of chemicals, including acids, alkalis, organic solvents, paints, mineral fertilizers, pesticides, etc. from the territories of industrial and agricultural enterprises;
- flushing from the territories of cemeteries, unauthorized burials of people and animals, cesspools, septic tanks, cattle cemeteries, and landfills.

In addition, the destruction of the Kakhovka reservoir led to the following phenomena [11,12]:

- massive fish kills and death of aquatic life after the water runoff;
- the formation of large areas of bare bottom, from which inorganic and organic chemicals of various compositions will be released into the Dnipro River for a long time.

Our conclusions regarding the possible risks of a threatening deterioration in water quality are comparable to those set out in the report of the international organization OXFAM [13] "Hydrogeological Remote Desk Study – Kakhovka Reservoir Area – Ukraine", prepared after the destruction of the Kakhovka HPP. In addition to the damage to wastewater management systems, this report identifies the following causes of deterioration in natural water quality due to military operations:

- pollution of surface waters by sunken military objects (which in turn can contaminate any interconnected aquifer systems);
- release of chemicals due to shelling;
- overflooding of mines and minewaters due to damage to dewatering pumping equipment casing increased salt content, mineralization and heavy metal concentrations;
- bacteriological pollution due to mass poultry deaths;
- flooding associated with the bombing of reservoirs and dams e.g. the recent Kakhovka dam attack.

Further potential threats to water quality that have also been identified within the same study include:

- damage to nuclear power plants by low-flying missiles which can potentially damage cooling ponds, spread radioactive dust and materials into environment etc;
- explosions of containers containing chemicals at industrial sites or wastewater plants releasing large volumes of toxic chemicals into the environment which can infiltrate into groundwater systems (e.g. chlorine, fertilizer (ammonium, nitrate), hydrocarbons, potash);

- underwater decomposition of ammunition leading to release of heavy metals and toxic explosive compounds, which will be incredibly critical in the study area due to vast irrigation channel networks being in existence.

Deterioration of water quality in the area of drinking water intakes can lead to a decrease in the efficiency of existing drinking water treatment facilities. This may result in a situation where the quality of drinking tap water does not meet the current hygienic requirements in Ukraine [14], which threatens human health and life.

Considering the urgency of solving the problems of drinking water supply to the population, in particular, the safety and quality of drinking water, it is necessary to provide water utilities with an effective system of timely and adequate response to chemical, biological and radiation-nuclear (CBRN) water contamination.

This paper identifies the basic principles for developing a Response Plan for chemical, biological and radiation-nuclear emergencies caused by water pollution and organizing CBRN monitoring of water contamination.

2. Basic principles for developing a Response Plan for CBRN water contamination

When assessing and countering the consequences of emergency situations related to chemical, biological, radiation and nuclear water contamination, it is necessary to take into account that it is a potentially fatal chemical poisoning, bacterial contamination or radioactive / nuclear water contamination [15, 16].

The general flowchart of the Response Plan for CBRN water contamination emergencies is shown in figure 1.

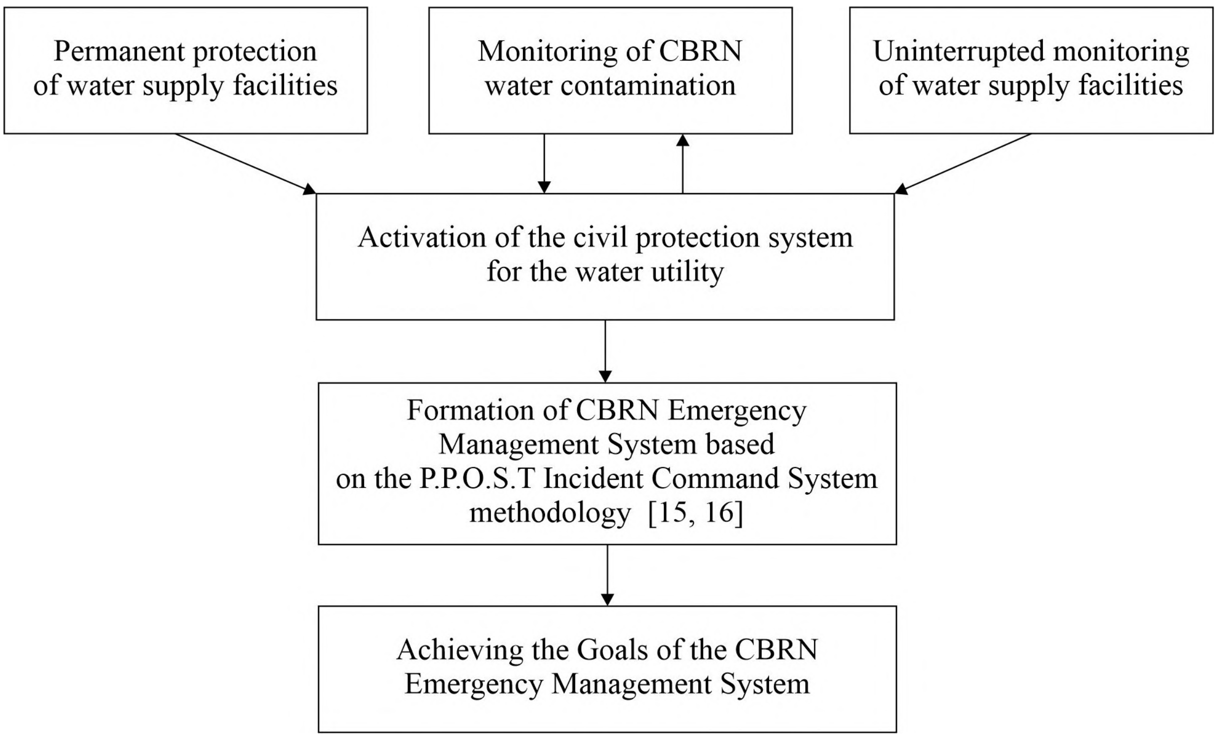

Figure 1. Flowchart of the Response Plan for CBRN water contamination emergencies.

The proposed structure of the Response Plan for CBRN water contamination emergencies provides for:

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1. Permanent protection of water supply system facilities.
2. Continuous monitoring of probable sites of possible CBRN contamination of water.
3. Monitoring of CBRN contamination of water in places where it is likely to enter the drinking water supply system.
4. Activation of the water utility's civil defence system in the event of unauthorized entry into the water supply system and/or detection of CBRN contamination of water.
5. Formation of the CBRN Water Contamination Emergency Management System [17,18] and achievement of the set goals.

The first task is directly related to the organization and functioning of the system of physical protection of water supply facilities. This system operates continuously and is not exclusive to emergencies involving CBRN water contamination. However, in case of a probable CBRN threat, this system should be guided by the following basic rule: any unauthorized access to a water supply facility, including sources of drinking water supply, must be evaluated from the point of view of possible entry of CBRN contamination into drinking water.

The difficulty of solving this task lies in the fact that the water utilities are not able to independently effectively counter the enemy's intentions to use CBRN-based weapons of mass destruction (WMD) against the water utility.

Therefore, the main attention should be paid to the third element – monitoring of CBRN water contamination, which should be carried out on the basis of a national operational system of laboratory control of water quality, in which the role and tasks of water utilities should correspond to their real technical capabilities. A general flowchart of CBRN water contamination monitoring is shown in figure 2.

First of all, water utilities must carry out on-line monitoring of water quality at water supply system facilities according to the main indicator parameters, which can be measured by hardware, without the constant presence of personnel. In the case of a sudden change in any of the indicators, the system issues an alarm signal about a possible threat of CBRN water contamination.

When confirming the reliability of the alarm signal from the on-line water quality monitoring system, the entire operational system for determining CBRN should be connected.

Since there is no such operational system in Ukraine, one of the tasks of this work is to develop the basic principles of its organization and technical and methodological support.

The following was taken into account during the development of the system of operational identification of CBRN water contamination:

1. It is impossible to work with CBRN-based WMD in the departmental laboratories of water utilities, as this will lead to the presence in the laboratories of a significant number of WMD elements in the form of standard samples of toxic substances, reference strains of pathogenic microorganisms, calibration sources of ionizing radiation, which are necessary for metrological support of the measurement process.
2. The list of toxic chemicals hazardous to humans, which, if released into water, can disrupt the water supply system, is so extensive that it is impossible to organize comprehensive laboratory monitoring on the basis of a single water utility.
3. To work with the most dangerous microorganisms of the I-II groups of pathogenicity in Ukraine, it is necessary to comply with the requirements of the DSP No. 9.9.5.035-99 [19]. It is practically impossible for the laboratories of the water utilities to completely fulfill these requirements, therefore they do not have the right to work with the biological component of weapons of mass destruction.
4. Radiological control of water quality after the accident at the Chernobyl NPP at water utilities corresponds to possible nuclear threats.

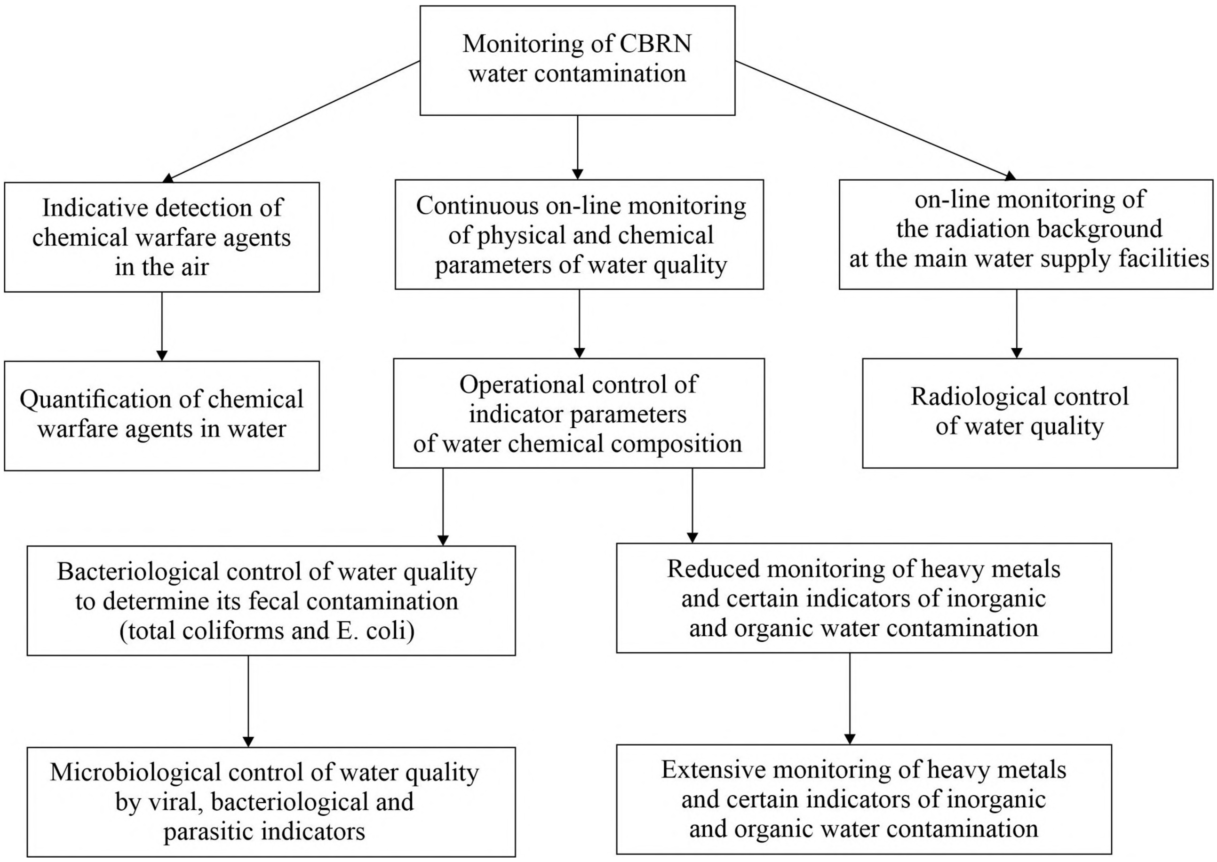

Figure 2. Flowchart of CBRN water contamination monitoring.

5. CBRN water pollution can be carried out both as a result of direct use of WMD, and through destroyed industrial, agricultural and private facilities, on which CBRN elements were concentrated.

3. Technical and methodological support for CBRN water contamination monitoring

Radiation monitoring of water quality after the accident at the Chernobyl NPP at the Ukrainian water utilities is organized at an appropriate level and corresponds to possible radiation threats to the quality of drinking water.

It is only necessary to pay special attention to the need to organize monitoring of the radiation situation, in particular, in the area of water intakes and at water treatment facilities by means of continuous measurement of the level of gamma radiation in the environment.

Radiation monitoring is also a mandatory component when conducting radiation and chemical reconnaissance of the territory that is critical for centralized water supply, affected by weapons of mass destruction or particularly dangerous non-combat substances, about which the water utility must receive information from the relevant authorized and competent services (SES, Armed Forces, etc.).

Biological monitoring of water quality involves the determination of biological pathogenic agents (BPA). In DSP 9.9.5-080-02 [20] it is indicated that "BPA are microorganisms pathogenic to humans (bacteria, viruses, chlamydia, rickettsia, protozoa, fungi, mycoplasma), genetically engineered microorganisms, poisons of biological origin (toxins), helminths that can cause disease, intoxication or death of a person or animal, as well as material (including blood, other biological fluids and body excreta) suspected of containing the listed agents".

Centre for Disease Control and Prevention of the United States defines four levels of classification of laboratories that act in the event of a threat of bioterrorist attacks [21–23]. These levels are classified from 1 to 4 (depending on the level of danger of the microorganisms that are studied in the laboratory), and they determine the necessary level of biological safety of the laboratory (BSL), that is a series of measures designed to protect the personnel of the laboratory, as well as the environment and the population [22].

A BSL-1 (lowest biosafety level) laboratory is a basic laboratory specializing in the study of non-lethal microorganisms that pose a minimal potential threat to laboratory workers and the environment.

A specialized research laboratory dealing with potentially deadly infectious agents such as the Ebola virus is defined as BSL-4 (the highest and most stringent level).

Knowledge of the difference in levels of biosafety laboratories and the corresponding safety requirements for them is mandatory for anyone who works with microorganisms in a laboratory setting.

Laboratories of Ukrainian water utilities belong to the lowest level of biosafety, so they have the right to determine only opportunistic microorganisms, for example, Escherichia coli, which is an indicator of fecal contamination of water. Approved in April 2022, the State Sanitary Rules and Regulations for Drinking Water Quality [14] recommend using Colilert-18 tests manufactured by IDEXX (USA), which several dozen water utilities have experience with.

Chemical monitoring of water quality should be organized both for the quick determination of the presence of combat toxic substances and for the constant monitoring of chemicals of "peaceful" (industrial, agricultural, household) origin.

The need to determine combat toxic substances is established on the basis of information received from the competent authorities - the State Emergency Service or the Armed Forces. Like radiation monitoring, such determination is also a mandatory component of radiation and chemical reconnaissance of the territory that is critical for centralized water supply.

In order to establish the fact of the enemy's use of combat toxic substances and their possible contamination of drinking water, [14] indicate the possibility of using a military chemical intelligence kit of the VKHR type. The kit includes indicator tubes through which air is pumped from the affected area. In the case of the presence of poisonous substances in the air, the colour of the tube filler changes, which roughly determines the concentration of these substances. The codes of the indicator tubes for determination of chemical warfare agents are given in table 1.

Table 1. VKHR indicator tube codes for determination of chemical warfare agents.

№	Code of the indicator tube	Type of chemical warfare agent	Sensitivity, mg/m^3
1	DT-11	GB, GD, VX (sarin gas, soman, V-gases)	0.05
2	DT-12	CG, CK, AC, DP (phosgene, diphosgene, hydrocyanic acid, chloroacetic acid)	5.0
3	DT-15	HD (mustard gas)	1.0

It is clear that the determination of combat toxic substances in the air is not a confirmation of their contamination of drinking water but indicates the possibility of such contamination. In any case, if the use of chemical warfare agents is confirmed, for example, in the water intake area, this will mean that water intake will have to be suspended until the situation with water contamination is clarified.

The VKHR kit can also be equipped with indicator tubes for detecting non-combat (industrial, agricultural, etc.) hazardous chemicals in the air (table 2).

Table 2. VKHR indicator tube codes for identifying industrial hazardous substances.

№	Code of the indicator tube	Type of chemical warfare agent	Sensitivity, mg/m^3
1	DT-001	Phosgene	0.5
2	DT-002	Hydrocyanic acid	3.0
3	DT-003	Chlorine	3.0
4	DT-004	Sodium oxide	2.0
5	DT-005	Sulfur dioxide	1.0
6	DT-006	Sulfonamide	5.0
7	DT-007	Sulfur dioxide	20.0
8	DT-008	Ammonia	50.0
9	DT-009	Hydrogen chloride	10.0
10	DT-010	Formaldehyde	0.5
11	DT-011	Carbon monoxide	30.0

Continuous monitoring of non-combat hazardous chemicals in water is proposed to be organized in four stages.

Stage 1. Continuous on-line monitoring of physical and chemical parameters that can change when water quality deteriorates, such as electrical conductivity, pH value, redox potential, turbidity, colour, and free chlorine concentration.

Since the World Health Organization (WHO) recommends [24] to establish continuous on-line monitoring of the indicated parameters at the main water supply facilities, it is planned to measure them also for all water samples that are examined at the next stages of monitoring.

This stage of monitoring is crucial for deciding whether to deploy more detailed water quality analysis.

It is recommended to consider a reliably established change of one of the indicated parameters by 15% during a time of less than 15 minutes as a basis for strengthening monitoring. For example, if the pH value was 7.5, but quickly began to change and in less than 15 minutes went beyond the interval of 6.5-8.5, then this is a reason for expanding monitoring. It is also necessary to pay attention to the possible change of other online indicators, even if they did not go beyond the 15% interval.

To increase the effectiveness of on-line monitoring, it is necessary to establish at least 2-3 consecutive control points at one water supply facility, and a sharp change in any of the indicators at several points should be considered a sufficient reason for deploying monitoring and finding the reason for the change in the parameter.

The dispatch service and management of the water utility are immediately informed about the confirmed operation of the on-line monitoring system and the need to deploy operational monitoring.

Stage 2. Operational monitoring of indicator parameters of the chemical composition of water (table 3), which are determined by the EU Drinking Water Quality Directive [25] and supplemented by the indicators specified in [14].

Table 3. Indicator parameters of operational water quality monitoring.

№	Parameter	Unit	Parametric value
1	Taste		Acceptable to consumers and no abnormal change
2	Colour		Acceptable to consumers and no abnormal change
3	Odour		Acceptable to consumers and no abnormal change
4	Turbidity		Acceptable to consumers and no abnormal change
5	Hydrogen ion concentration	pH units	6.5-9.5
6	Conductivity	µS/cm at 20°C	2500
7	Total hardness	mmol/l	7.0
8	Total alkalinity	mmol/l	6.5
9	Aluminium	µg/l	200
10	Ammonium	mg/l	0.5
11	Chloride	mg/l	250
12	Iron	µg/l	200
13	Manganese	µg/l	50
14	Sulphate	mg/l	250
15	Sodium	mg/l	200
16	Oxidisability	mg/l O_2	5
17	Chemical oxygen demand	mg/l O_2	no abnormal change
18	Total organic carbon		no abnormal change

Also at this stage, bacteriological control of water quality is carried out to determine fecal contamination (total coliforms and E. coli), for which [14] recommends using Colilert-18 IDEXX tests.

It is possible to carry out daily operational monitoring of the quality of natural, drinking and waste water in all settlements of Ukraine, including in emergency situations, with the help of a mobile chemical and bacteriological laboratory [26], which is equipped on the basis of a 7500 Palintest photometer (England) and bacteriological equipment IDEXX (USA).

Such mobile laboratories should be located in places where, no later than 30 minutes after establishing the fact of a sharp change in the on-line indicator, it is possible to start water quality monitoring based on indicator parameters for water samples taken at on-line monitoring points.

It is recommended to keep one mobile laboratory ready at water treatment facilities and to have at least one laboratory for traveling to water supply facilities.

The list of indicator parameters that are measured first is determined by which of the on-line indicators has changed dramatically and which indicators have also changed.

For example, if there is a sudden change in the concentration of residual free chlorine, it is imperative to check the indicators of organic contamination of water, as well as the concentration of ammonium and iron. In case of changes in electrical conductivity, it is necessary to check the salt composition of the water. If the redox potential decreases, it is necessary to check the ammonium concentration as an indicator of drinking water contamination by wastewater.

Stage 3. Shortened monitoring of the content of heavy metals and individual indicators of inorganic and organic water pollution [14] (table 4).

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Table 4. Parameters of shortened water quality monitoring [14].

№	Parameter	Unit	Parametric value
1	Nitrate	mg/l	50
2	Nitrite	mg/l	0.5
3	Fluoride	mg/l	1.5
4	Cyanide	µg/l	50
5	Copper	mg/l	1.0
6	Zinc	mg/l	1.0
7	Volatile phenols	µg/l	1.0
8	Chloroform	µg/l	60
9	Trihalomethane (sum)	µg/l	100
10	Oil products	µg/l	100
11	Surfactants anionic	µg/l	500

To determine the indicators specified in tables 3 and 4, the water utility laboratory should be equipped with the following analytical equipment: spectrophotometer, fluorometer, gas chromatograph, AAS analyzer and TOC analyzer.

Stage 4. Expanded monitoring of the chemical, microbiological and radiological composition of water – the content of heavy metals and certain indicators of inorganic and organic water pollution (table 5), microbiological indicators and radioisotope composition – are determined.

The first three stages of water quality monitoring, as well as the determination of some heavy metals included in the Stage 4, can be carried out by the water utility's laboratory with proper technical, methodological and personnel support. The fourth stage of monitoring is carried out on the basis of state specialized toxicological, microbiological and radiological laboratories supplied with the necessary analytical equipment and methodological support and authorized to work with particularly hazardous substances, biopathogens and radioisotopes.

The cost of laboratory equipment for determining water composition at this stage is several million euros, and therefore it makes no sense to equip water utility laboratories with it. It should also be kept in mind that water utility laboratories do not have the financial capacity to hire highly qualified specialists capable of working with such equipment.

Water samples for analysis at all 4 stages are collected with the participation of specialists from the water utility's laboratory, but at the Stage 4, they must be instructed on the rules of sampling by a representative of a specialized laboratory, depending on the type of analysis.

The main characteristics of the stages of CBRN water contamination monitoring are presented in table 6. The general algorithm for CBRN water contamination monitoring is shown in figure 3.

To implement CBRN water contamination monitoring within the first three stages, a list of additional analytical and auxiliary laboratory equipment, consumables and reagents was compiled in the laboratory of the water supply and sewerage enterprise.

The calculation was made for one year of laboratory operation, assuming that the on-line monitoring system is activated on average once a week. The estimated cost of organizing such monitoring is 893 thousand euros.

Also, based on this list, a preliminary estimate was made of the operating costs for organizing and conducting CBRN water contamination monitoring, which amount to about 464 thousand euros.

Table 5. Parameters of expanded water quality monitoring.

№	Parameter	Unit	Parametric value
1	Boron	mg/l	1.5
2	Bromate	µg/l	10
3	Lead	µg/l	5
4	Mercury	µg/l	1
5	Nickel	µg/l	20
6	Antimony	µg/l	10
7	Arsenic	µg/l	10
8	Cadmium	µg/l	5
9	Chromium	µg/l	25
10	Selenium	µg/l	20
11	Acrylamide	µg/l	0.1
12	Benzo(a)pyrene	µg/l	0.005
13	Pesticides	µg/l	0.1
14	Chlorophenols	µg/l	0.3
15	Pesticides Total	µg/l	0.5
16	Benzene	µg/l	1
17	Carbon tetrachloride	µg/l	2
18	1,2-dichloroethane	µg/l	3
19	Dibromochloromethane	µg/l	10
20	Tetrachloroethene and Trichloroethene	µg/l	10
21	Formaldehyde	µg/l	50
22	Polycyclic aromatic hydrocarbons	µg/l	0.1
23	PFAS Total	µg/l	0.5
24	Sum of PFAS	µg/l	0.1
25	Epichlorohydrin	µg/l	0.1
26	Microcystin-LR	µg/l	1
27	Haloacetic acids (HAAs)	µg/l	up to 60
28	Bisphenol A	µg/l	up to 2.5

4. Conclusions

Ensuring the safety and quality of drinking water is a crucial task, especially in the context of martial law and the possibility of damage to water sources, water treatment facilities, water networks, and other water supply and sewerage facilities and deterioration of tap water quality. To ensure an effective system of timely and adequate response to various types of water contamination, several measures should be taken:

- develop emergency response plans in the event of chemical or radiation releases, as well as biological contamination. These plans should identify procedures, responsible personnel, and use advanced technology to quickly identify and correct problems;
- as part of the implementation of the Response Plan for CBRN water contamination emergencies, monitor water quality in water supply sources and water networks to detect any changes in the level of chemical, biological, radiation and nuclear contamination;
- use modern technologies, such as automated monitoring systems, sensors, and rapid pollution detection systems, which allows for prompt detection of problems and real-time response.

Table 6. Main characteristics of the stages of CBRN water contamination monitoring.

No. of stage	Stage name	Indicators to be determined	Control points	Sample collection	Location of the analysis
	Radiation and chemical reconnaissance	Environmental radiation background, chemical warfare agents, particularly hazardous non-combatants	Determined on the basis of information on WMD from competent state services	Specialists of the competent services with the participation of the water utility laboratory	At control points
1	Continuous on-line monitoring of physical and chemical parameters	Electrical conductivity, pH value, redox potential, turbidity, colour, free chlorine	Key facilities of centralized water supply (water intake, clean water tank, water supply network, etc.)	Automatically	On-site installation of on-line monitoring systems
2	Operational control of indicator parameters of water chemical composition	Table 3, total coliforms and E. coli and on-line monitoring indicators (Stage 1)	First, at the on-line monitoring points from which the alarm came, then according to the situation	Water utility laboratory	On-site installation of on-line monitoring systems and / or in the water utility's laboratory
3	Reduced control of water chemistry	Table 4 and on-line monitoring indicators (Stage 1)	Based on the results of the previous stage	Water utility laboratory	In the water utility's laboratory
4	Extensive control of the chemical, microbiological and radiological composition of water	Chemical warfare agents, toxic compounds that pose a potential threat to water quality, biological warfare agents, table 5, on-line monitoring indicators (Stage 1), radioisotopes	Based on the results of the previous stage and radiation and chemical reconnaissance	Specialized toxicological, microbiological and radiological laboratories with the participation of the water utility's laboratory	In a specialized laboratory

It is also necessary to ensure effective crisis management through training of water utility personnel, cooperation with authorities, scientific institutions and local residents to identify potential threats and jointly address water supply problems.

These measures will contribute to the creation of a system that will ensure an effective and adequate response to chemical, biological, radiation-nuclear water contamination, which is important for ensuring the safety and quality of drinking water for the population.

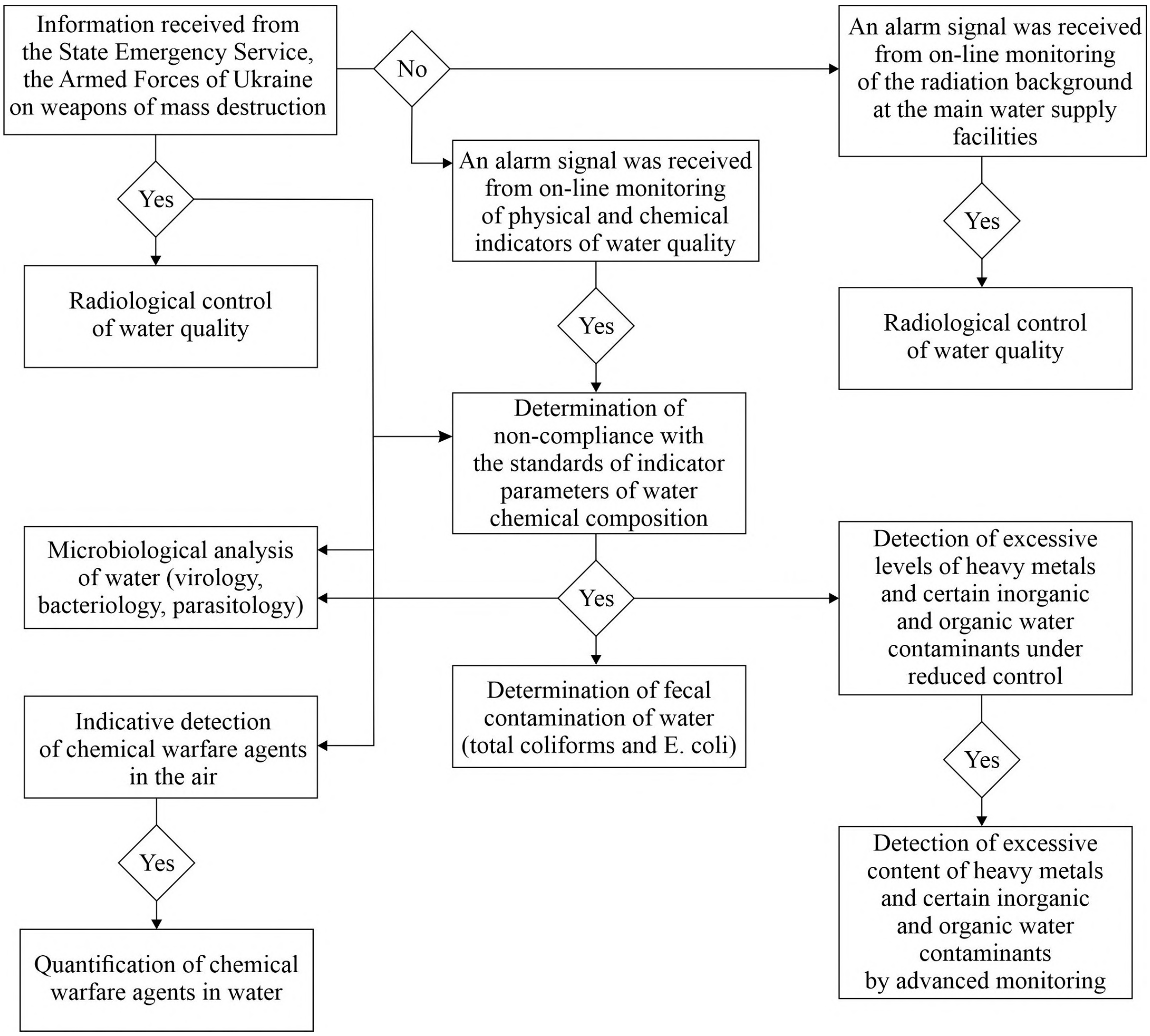

Figure 3. Algorithm for CBRN water pollution monitoring.

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The influence of the accident at Chernobyl nuclear power plant on the condition of pine plantations of Ukrainian forests

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Abstract. The article analyzes the distribution of trees according to the main ecological indicators that characterize the viability of artificial pine stands, in which forestry activities were stopped due to significant radioactive contamination, 35 years after the accident at the Chernobyl nuclear power plant. In intensively polluted areas and control trial areas in fresh forests, the following distribution of trees by categories of sanitary condition was noted: healthy pine trees (category I) make up 29–33 percent and 47–53 percent of the total number of trees, respectively, weakened (category II) – 29–33% and 29–37%, very weakened (III category) – 13–17% and 6–12%, the share of dying and dead trees (IV–VI status categories) is 22–24% and 9–12%. It can be emphasized that in the same studied types of forest vegetation conditions, where the levels of radioactive pollution allowed to carry out forestry activities, a much better sanitary condition of pine stands was noted. Analyzing the indicators of the general index of the sanitary condition of pine plantations in the zone of unconditional resettlement, it can be noted that all stands belong to very weakened ones, the index is in the range from 2.45 to 2.55. In the control test areas, where forestry measures for the care of stands were carried out in a timely manner, this indicator was lower – by 13-26%. The study of the process of formation of waste and drying of pine stands shows that the share of trees of IV-VI categories of sanitary condition in fresh forests is 22-24%, and this is almost a third of trees that, as a rule, will die within a few years. In addition, trees of category III (13–17%) pose a significant threat, which will move into lower status categories without forest management measures. Research results show that after the cessation of forestry activities in the zone of unconditional resettlement, there is an intensive accumulation of dryness and a significant weakening of tree stands. In the radioactively contaminated territories, almost 58 to 70% of the trees are belonging to the II and III categories of technical suitability, and in the control areas the share of trees of the I category ranges from 45 to 64%.

1. Introduction

The forest massifs of the Ukrainian Polissia are represented, in the vast majority, by forest crops of Scots pine (Pinus sylvestris L.) [1, 2]. Growth characteristics and productivity of such plantations depends on the biological characteristics of the species and resistance to environmental conditions of growth, which, in turn, is directly related to the implementation of timely and highly qualified forestry measures. All forestry enterprises of the Zhytomyr region are characterized by the proper implementation of forestry measures, which contributed to the maintenance of the optimal state of forests and the formation of high-quality stands [3, 4]. However, as a result of the accident at the Chernobyl nuclear power plant, part of these forest areas were exposed to radioactive contamination and were withdrawn from forestry use. Pine plantations of different age groups were left unattended for a long time. In connection with this, negative changes began to be traced in them. Favorable conditions for the development of pests and diseases were created, the fire hazard increased, the quality of wood decreased, the processes of self-liquefaction of stands accelerated, accumulation of dry matter and the formation of litter increased. In general, the processes of degradation of artificial pine plantations have begun.

For tree stands in the area of radioactive fallout, an increase in the share of stands with disturbed stability was noted, and the intensity of growth of pine stands increased significantly [5–7]. Researchers [8–10] noted that in the forest vegetation conditions of a fresh forest, the tendency to the deterioration of the state of plantations was more pronounced than in the conditions of a wet forest, fresh and wet forest. The processes of self-liquefaction and accumulation of waste accelerated. The rates of accumulation of waste are higher in high-quality young animals and medieval cultures and depend on the conditions of local growth [11]. As a result of the transition of stands to older age groups, there is a decrease in the number of trees per unit area, which causes accumulation of dryness. This leads to an increase in the cluttering of plantations, roads and canals, as a result of which a 1.5-2 times increase in the density of pine plantations was noted [7]. Under the forest canopy, stocks of forest litter increase, dead needles, leaves, small branches, bark accumulate, which slowly decompose, but burn very well, and create an additional fire hazard [12]. As a result of the restriction of economic activity in radioactively contaminated pine plantations, productivity decreased, the sanitary condition worsened, the number of trees of IV–VI status categories increased, and the number of trees of I–III categories decreased [5, 9, 13]. In radioactively contaminated territories, the sanitary condition of young trees and medieval stands is the most threatening. A natural, significant deterioration of the condition index of pine stands is observed, starting from 81–100-year-old to 1–20-year-old young trees and to stagnant stands [14]. The phytosanitary situation has significantly deteriorated, favorable conditions for the spread of pests and diseases have been created [15].

It is known that after entering the components of forest ecosystems, radionuclides gradually moved from the upper to the lower layers of vegetation and the soil surface. Directly under the influence of precipitation and wind, as well as due to the fall of leaves, needles, branches and bark, their vertical and horizontal migration took place [16, 17]. The duration of vertical migration in the crown-litter-soil-root chain, during which up to 95% of radionuclides move from the crown to the forest floor, is approximately one year in deciduous stands, and up to 3 years in conifers [16], and according to others estimates – from 3 to 7 years [18]. After the movement of radionuclides to the forest floor and depending on the type of forest vegetation conditions and the composition of the tree layer, the migration of radionuclides of different intensity began in the genetic horizons of forest soils [19–25].

Scots pine (Pinus sylvestris L.) is the most common species in forests that have experienced significant radioactive contamination and belongs to wood species that are quite plastic in terms of ecological requirements. The researchers noted that coniferous tree species are 5–10 times more sensitive to radiation exposure than hardwoods [16], and accumulate radionuclides 2–3 times more [18] compared to them. That is why pine plantations can be used as an indicator of contamination of the ecosystem with radionuclides in the process of assessing and forecasting the sanitary condition of forest areas in radioactively contaminated territories.

More than 35 years have passed since the accident at the Chernobyl nuclear power plant, and the radiation situation in forest areas has changed. That is why it is necessary to carry out a modern assessment of the sanitary state of pine plantations in radioactively contaminated territories. The obtained results will provide an opportunity to consider ways of optimizing forestry management in radioactively contaminated territories, which will contribute to improving the condition of stands on these lands.

2. Methodology

In order to assess the sanitary condition of pine plantations, test plots were laid out in the fresh forests of the Narodychi Forestry of the State Enterprise (SE) "Narodychi Specialized Forestry", where forestry activities were completely stopped due to high levels of radioactive soil contamination, and in the Malyn Forestry of the SE "Malyn Forestry", where timely forestry measures for forest care (figure 1). Test areas were established according to generally accepted methods in forestry and ecology. The research is based on the classical method of comparative forest ecology with its detailing according to individual ecological and forestry areas.

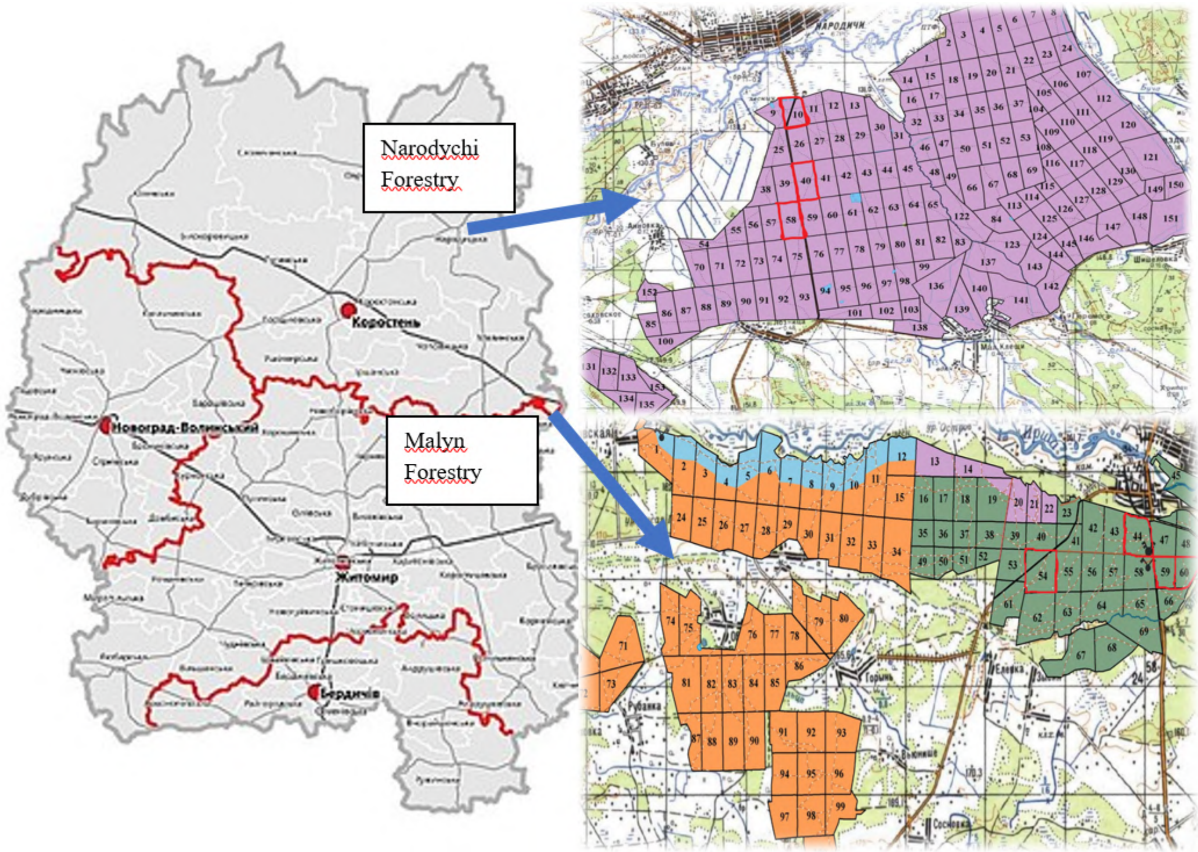

Figure 1. The studied region.

Assessment of the sanitary condition of pine stands on radioactively contaminated and control trial plots of the studied type of forest vegetation conditions, the actual taxing indicators of the plantations were determined using standard methods. Thus, after laying out the trial areas, a full description of tax indicators was carried out, which includes the following indicators: origin of plantations, shape, composition, average height, age, elements of the forest, bonity, fullness, average diameter, reserve, marketability class, type of forest. Each plot consisted of 100 trees. Recalculation of trees was carried out by measuring their diameters at a height of 1.3 m from the neck of the root. The minimum diameter of the trees that were included in the recalculation was more than 8 cm. The height measurement was based on the measurement of the heights of 30 trees, which were distributed according to the degrees of change in the diameter of the plantations (the measurement of the trees with the most frequently repeated diameter, in the direction of increase and decrease), i.e. stepwise. Determining the age of the main element of the forest is determined by counting the annual rings on the cores. For this, cores were taken to determine the age of the trial area with the help of an age drill. The origin of plantations was determined by forest tax records, in which it was indicated which plantation it was: natural or artificial, seed or sprout. The composition of the plantations is determined by the list of tree species that make up the stand, with an indication of the share of each species in the total stock. The quality of a forest can be determined by the total stock of wood or by its average growth, but the most widely used indicator of forest productivity is the average height of the trees of the first tier of the forest stand at a certain age. Knowing the average height and age of the trees, they can find the standing's standing according to the tables of standing classes. The completeness and stock of plantations was obtained by the calculation method, after the analysis of the tax indicators listed above. An assessment was also carried out according to the marketability class of wood according to categories of technical suitability. Clutter was taken into account separately, dividing it into liquid and non-liquid wood.

The sanitary condition of pine plantations was assessed according to the condition index (I) of the first tier of stands, which was calculated according to the methodology of the Ukrainian Research Institute of Forestry and Agroforestry named after G. M. Vysotskiy on a 6-point scale [26, 27]:

$$I = \frac{(i_1 n_i) + (i_2 n_i) + (i_3 n_i) + (i_4 n_i) + (i_5 n_i) + (i_6 n_i)}{N}$$

where: I – forest condition index, $i_1 - i_6$ – tree condition categories (from I to VI), n_i – the number of trees of the same state category, individuals, N – total number of assessed trees on the trial area, individuals.

Stands with an index of 1.00–1.50 are considered healthy (no damage); weakened – 1.51–2.50 (damage is weak); severely weakened – 2.51–3.50 (damage is average); those that dry out – 3.51–4.50 (severe damage); dead – 4.51–6.00 (the damage is very strong).

This technique most accurately characterizes the current state of pine plantations in the forest areas of Ukraine.

3. Results

The decline in the viability of pine stands in the zone of unconditional resettlement is largely characterized by the distribution of trees by categories of sanitary condition. In the Narodychi Forestry, where the level of radioactive contamination of the soil did not allow any forestry activities to be carried out, the range of variation of the specific weight of individual categories of trees fluctuated significantly. Healthy pine trees (category I) accounted for 29 to 33%, weakened pines (category II) – 29–33%, very weakened (category III) – 13–17%, drying and withered (categories IV–VI) – 22– 24% of the total number of trees. In the Malyn Forestry, where the level of radioactive contamination is low and full-fledged forestry work was carried out in a timely manner, the sanitary condition of trees is much better: I category – 47-53%, II – 29-37%, III – 6-12%, IV-VI – 9 -12% of the total number of trees.

When analyzing the distribution of trees by status categories in medieval pine plantations (figure 2), it was noted that on permanent trial area (PTA) No. 4K the number of pine stands without signs of weakening (category I) is 1.2 times more than on PTA No. 4, and weakened (category II) – 1.1 times, respectively. Regarding the distribution of tree stands according to the III category, no significant difference was noted, however, the share of very weakened trees is 13% on PTA No. 4, and 12% on PTA No. 4K.

When comparing the percentage distribution of the following categories of sanitary condition, it can be noted that there are 1.7 times more dying stands of IV category on PTA No. 4 than on the control (PTA No. 4K), fresh dry ones (V category) – 3 times more, and old dryness (VI category) – 1.2 times. Therefore, according to the obtained results, it can be stated that

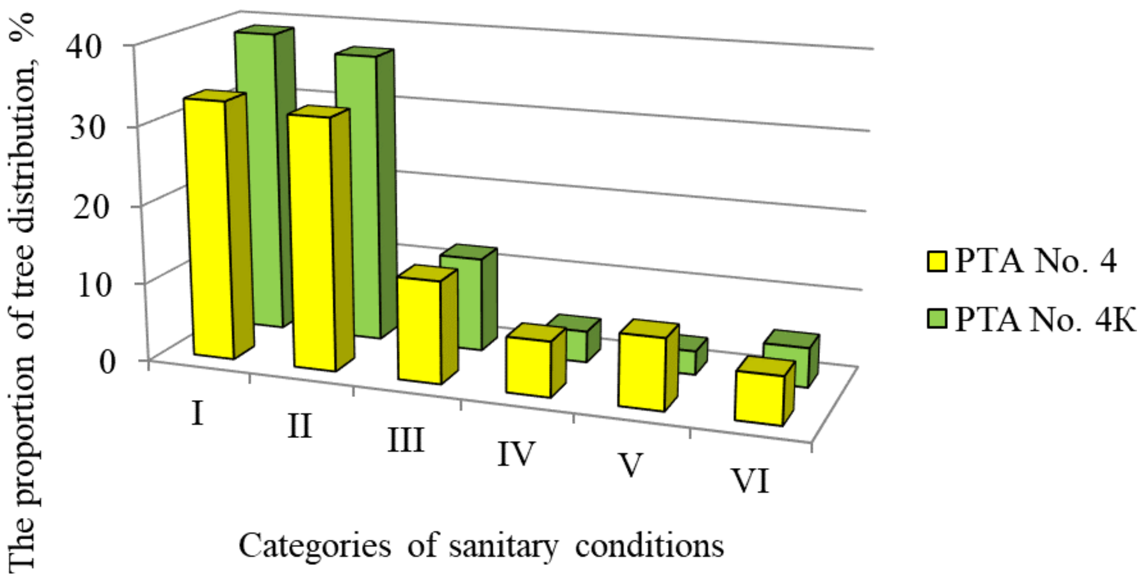

Figure 2. Distribution of trees in medieval pine stands by categories of sanitary condition in conditions of fresh pine.

in the 60-year-old forest plantations of the Narodychi Forestry, the distribution of stands by status categories is much worse than in the Malyn Forestry. Although, conducting a one-factor variance analysis of the distribution of trees by category of sanitary condition, no significant difference in mean values was found – $F_{fact.} = 3.0 < F_{(1;199;0.95)} = 3.9$.

The distribution of pine stands by status categories in the incoming plantations of fresh pine of the Ukrainian Polissia shows that there are 1.8 times more pine stands with no signs of weakening on PTA No. 5K than on PTA No. 5 (figure 3). However, the total percentage of weakened stands of the II category was the same and amounted to 29%. Analyzing the further distribution of stands, significantly higher indicators of deterioration of the state of plantations in Narodychi Forestry compared to the control were noted. Thus, the number of very weakened stands (category III) is 2.8 times greater on PTA No. 5 than on PTA No. 5K.

With regard to the distribution by other categories, a similar difference is observed, and the excess of the number of trees on PTA No. 5 in comparison with PTA No. 5K is: for IV category – 2.2 times, V category – 2.0 times, and old drywood (VI category) – 1.7 times. When conducting a one-factor variance analysis of the distribution of categories of the sanitary state of the arriving plantations, the existence of a reliable difference in the average values at the 95% confidence level was established: $F_{fact.} = 11.2 > F_{(1;199;0.95)} = 3.9$.

Analyzing the distribution of trees by categories of sanitary condition in mature pine stands, it was found that on the PTA No. 6 healthy stands (I category) are 1.6 times less than on the PTA No. 6K, and weakened ones (II category) are 1.1 times less, respectively (figure 4). The share of very weakened stands on PTA No. 6 is 14%, which is 2 times more than on PTA No. 6K. The analysis of the distribution of trees according to IV, V and VI categories is very important, because it makes it possible to reflect the processes of self-liquefaction of plantations. Thus, on PTA No. 6K, the distribution of trees by category was characterized by the following values: for IV – 3%, V – 1% and VI – 5%; while at PTA No. 6 these indicators are 3.3, 6.0, and 1.6 times higher, respectively. The obtained results of the difference between the categories of the condition of mature pine plantations are confirmed by the results of one-factor variance analysis: $F_{fact.} = 12.6 > F_{(1;199;0.95)} = 3.9$.

The general distribution of the studied stands shows that in radionuclide-contaminated

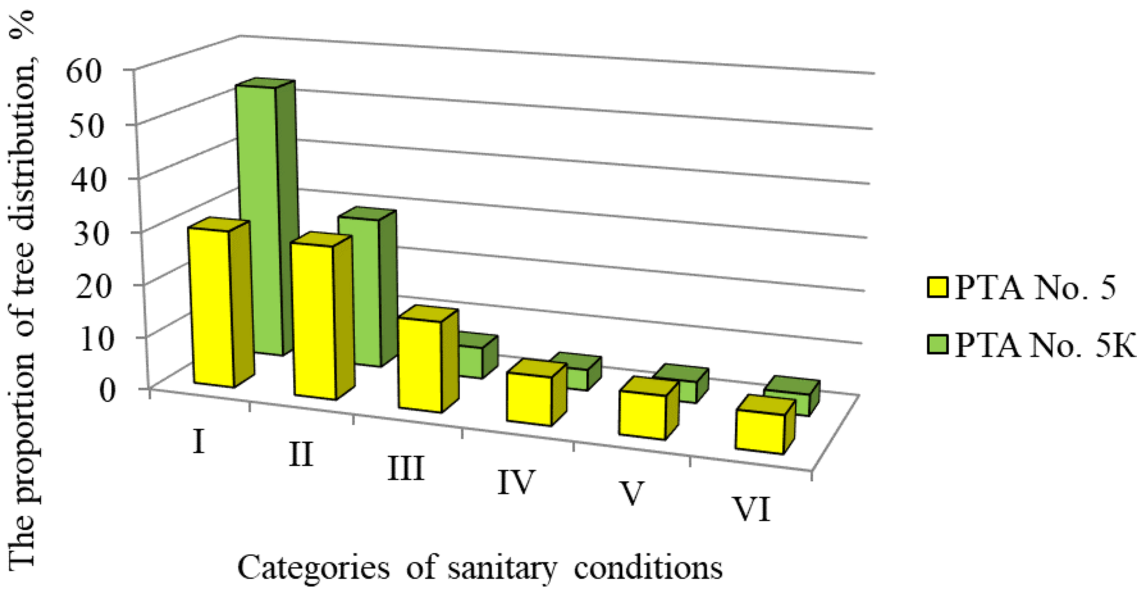

Figure 3. Distribution of trees in incoming pine stands by categories of sanitary condition in conditions of fresh pine.

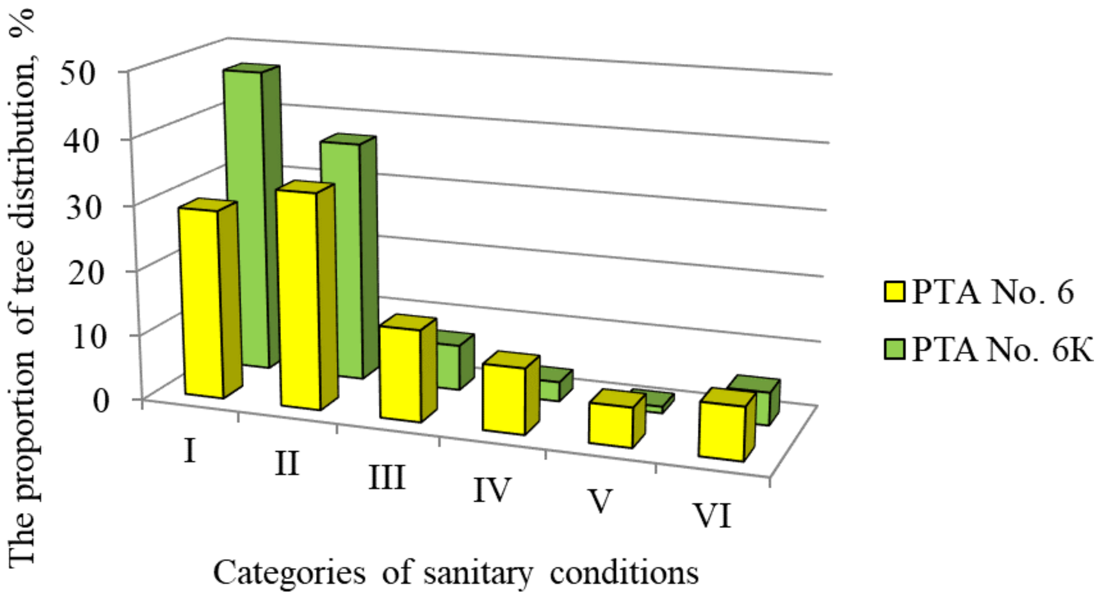

Figure 4. Distribution of trees in mature pine stands by categories of sanitary condition in conditions of fresh pine.

plantations of all age groups, the specific gravity of healthy pines is lower, and weakened and very weakened ones are much higher than in plantations outside the zone of radiation contamination. The obtained results are confirmed by the index of sanitary condition, which in the Malyn Forestry, where economic activity was carried out in a timely manner, ranged from 1.89 to 2.13, and in the Narodychi Forestry, it is in the range from 2.45 to 2.55.

In addition, the distribution of stands by marketability classes in the experimental plots was analyzed. It has been established that there are 1.2 times fewer trees belonging to the I class (business wood) on PTA No. 4 than on PTA No. 4K. The distribution by class II (semi-finished wood) is almost the same and amounts to 43 and 42%, respectively. However, during the analysis of the IIIrd class of marketability, it was noted that there is 1.7 times less firewood on PTA No. 4K than on PTA No. 4.

Similar patterns were observed on other test plots. Thus, the share of distribution of trees of the IIIrd class of marketability on PTA No. 5K and PTA No. 6K is 1.5 and 1.4 times less than on PTA No. 5 and PTA No. 6, respectively. On the control plots, the share of class I forest stands was 42% in PTA No. 5K and PTA No. 6K – 48%, while in PTA No. 5 and PTA No. 6 it was 1.5 times less. Analyzing the distribution of stands by marketability class, it can be assumed that the distribution of trees according to this indicator depends on the quality and timeliness of forestry activities.

The analysis of the obtained data shows that the specific activity of 137Cs in the components of the forest ecosystem differs significantly in fresh pines. The minimum values of the studied indicator were noted in the soil, and the maximum values were recorded in the forest floor and individual representatives of the grass-shrub and moss cover (figure 5).

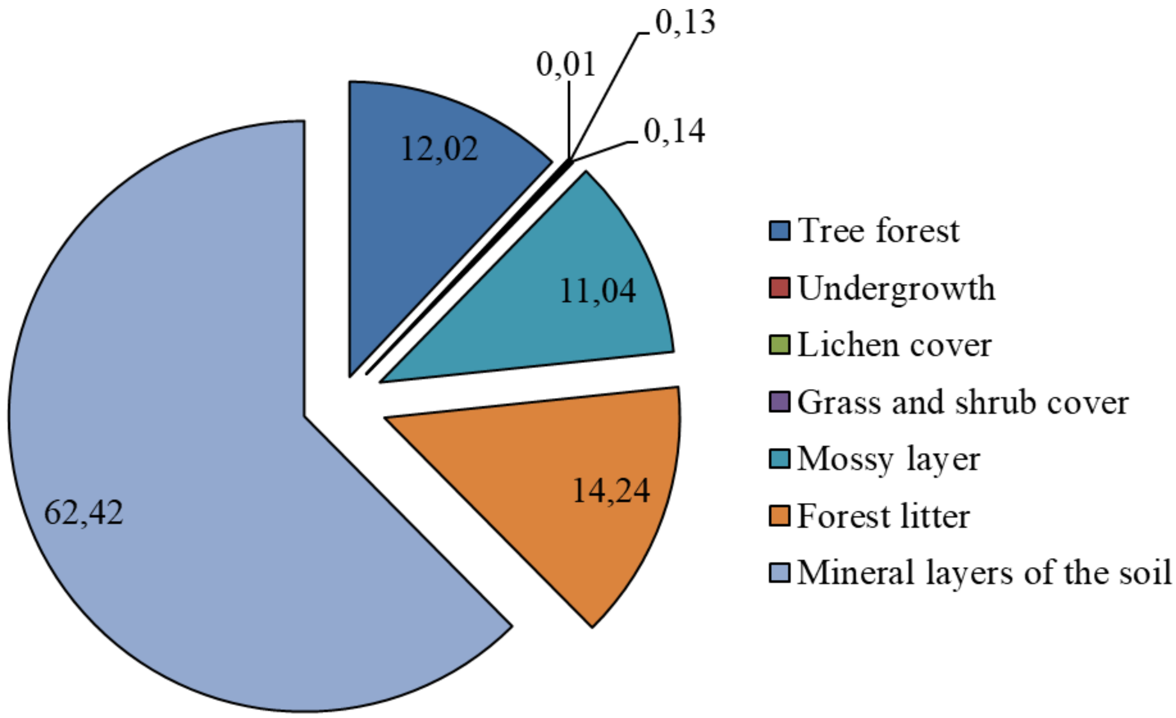

Figure 5. Share of the total activity of ^{137}Cs in the forest ecosystem of a pine forest under conditions of fresh boron, %.

During the analysis of the values of the specific activity of the radionuclide in pine, the usual highest indicator was noted in the inner bark, which is 2.0 times more than in the outer one, and the wood is characterized by the lowest values of ^{137}Cs content. According to the increase in the specific activity of the radionuclide in the morphological parts of the tree, the following ranked order can be established: $wood < thickbranches < thinbranches < outerbark < pins < innerbark < shoots$.

4. Conclusions

The following conclusions can be drawn on the basis of the conducted research:

1. The distribution of stands by categories of sanitary condition shows that in the Narodychi Forestry healthy pine trees (category I) accounted for 29 to 33%, weakened pines (category

II) – 29–33%, very weakened (category III) – 13–17%, drying and dry (IV–VI categories) – 22–24%. In the Malyn Forestry, I category stands account for 47–53%, II – 29–37%, III – 6–12%, IV–VI – 9–12% of the total number of trees.

2. The index of the sanitary state of pine plantations in the Malyn Forestry ranges from 1.89 to 2.13, which refers to the plantations as weakened, and in the Narodychi Forestry this index ranges from 2.45 to 2.57 and indicates a very weakened state of the plantations.
3. The obtained indicators of the distribution of stands by the class of wood marketability indicate that the proportion of category I trees in the Malyn Forestry is significantly higher compared to the Narodychi Forestry (PTA No. 4 – 38%, PTA No. 4K – 45%, PTA No. 5 – 28%, PTA No. 5K – 42%, PTA No. 6 – 32%, PTA No. 6K – 48%). At the same time, in radioactively contaminated territories, the share of II and III class stands is growing significantly.
4. The distribution of the radionuclide among the components of the artificial scots pine ecosystem in fresh pine shows that the main content of ^{137}Cs is concentrated in the forest soil – 76.66%, and the share of the total activity of the radionuclide in the phytocenosis is 23.34%. It has been established that the main role in keeping the radionuclide is played by the tree and moss layer. Yes, the above components contain ^{137}Cs: in fresh pines – 51.49% and 47.32%, respectively.
5. In order to preserve pine plantations, it is necessary to consider the possibility of resuming forestry activities in forest divisions in which they were prohibited, taking into account the current density of radioactive soil contamination. This requires an examination of forests for radioactive contamination based on an updated methodology using modern data on the study of the migration of radionuclides in forest soils.
6. The distribution of the radionuclide by the components of the artificial ecosystems of scots pine, wet undergrowth and fresh pine shows that the main content of ^{137}Cs is concentrated in forest soils – 74.06% and 76.66%, and the share of the total activity of the radionuclide in the phytocenosis is 25.94% and 23.34%, respectively. It has been established that the main role in keeping the radionuclide is played by the tree and moss layer. Thus, the above-mentioned components contain ^{137}Cs: 49.47% and 46.06% in wet pines, and 51.49% and 47.32% in fresh pines, respectively.

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Variable-structure controller design for electric drives with variable-torque load

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Abstract. The paper is devoted to the design of a framework to study uncertain nonlinear dynamical plants. We use the results of this study to design a variable-structure control system for the considered plants. Our studies are based on the use of interval methods to take into account possible plant parameters variations and perform a piecewise linear approximation of the plant's nonlinearity. We offer to replace a nonlinear function, which is used to define a plant's dynamic with a phase space domain where this function is localized. This allows us to rewrite the initial nonlinear differential equation into piecewise linear form and apply the Laplace-Carson transformation for the considered differential equation to define the generalized transfer function which gives us the possibility to study and design system dynamics. We use a determined piecewise linear interval transfer function to solve the inverse dynamic problem and define the controller's transfer function which allows for reaching the desired motion trajectories. We show the use of our approach and its benefits by designing a controller for a ventilator electric drive. Comparison of the designed control system with the known one allows us to claim its high accuracy and energy efficiency.

1. Introduction

The efficient control of electric drives [1], plays a pivotal role in various industrial applications [2, 3], contributing to advancements in automation [4–6] and energy management [7–9]. One particularly critical area is the integration of electric drives with ventilator loads [10], which finds extensive application in fields ranging from heating, ventilation, and air conditioning systems to industrial ventilation. The ability to regulate and optimize the performance of electric drives in conjunction with ventilator loads is essential for achieving energy efficiency, precise control, and system reliability [11].

The unique characteristics of ventilator loads, characterized by dynamic airflow demands and variable load conditions, present intricate challenges for control systems [12]. Addressing these challenges requires advanced control strategies that can adapt to the dynamic nature of ventilator-driven systems [13, 14]. Moreover, the pursuit of energy-efficient solutions aligns with the broader global initiative towards sustainable practices [15], making the study of electric drive control with ventilator loads both timely and significant.

Recent advancements in the field of electric drives with ventilator loads have been shaped by a multitude of studies focusing on control strategies, system optimization, and the integration of innovative technologies. The literature in this domain reflects a diverse range of approaches and methodologies, showcasing the ongoing efforts to address the challenges posed by the dynamic nature of ventilator-driven systems.

In this paper, we consider design of robust control system for elecctric drive with ventlator load by using interval methods to define electric drive model and take into account its nonlinearities and uncertainties. When we use this model to solve inverse dynamic problem and define robust controller transfer function. At last, we consider some example to show usage of our approach.

2. Interval model for electric drive with ventilator torque

Let us consider the use of our approach to design controller for electric drive with ventilator load. We continue our previous studies [16] and think that ventilator torque depends not only electric drive speed but operational and environmental conditions

$$\tau = T_0 + k_T \omega^a, \tag{1}$$

here T_0 is a constant, which defines an idling torque, k_T is a weight factor, ω is a drive speed, and a is a power factor, which is depend from electric drive operational conditions. It is known that this factor is defined in the interval $[1.5, 2.5]$ and its conventional value equals to 2.

We consider dynamic of an electric drive in the simplified way by assuming that its electromagnetic inertia is compensated by using internal currents and/or flux controllers

$$T_m \dot{\omega} = -\omega + k_d u - k_d^2 R \tau, \tag{2}$$

here T_m is an electromechanical constant, k_d is a drive gain, and R is a drive resistance.

Since the above-given motion equations is considered as equation in a normal form, we transform (2) into normal form by taking into account (1)

$$\dot{\omega} = -\frac{1}{Tm}\omega - \frac{k_d^2 k_T R}{T_m}\omega^a + \frac{k_d}{T_m}u - \frac{k_d^2 R}{T_m}T_0. \tag{3}$$

It is clear that dynamical plant (3) is a nonlinear plant with uncertain nonlinearity. That is why to simplify its studies we offer to take into account following relative units

$$w = \frac{\omega}{\omega_0},\ v = \frac{u}{u_m} = \frac{k_d u}{\omega_0},\ t_0 = \frac{T_0}{T_{max}} = \frac{k_d^2 T_0 R}{\omega_0}, \tag{4}$$

where ω_0 is an drive's idle speed, u_m is a maximal drive supplied voltage, T_{max} is a maximal drive torque
and rewrite (3) into dimensionless form

$$\dot{w} = b_1 w + b_{1a} w^a + m_1 v + m_0 t_0, \tag{5}$$

here

$$b_1 = -\frac{1}{T_m};\ b_{1a} = -\frac{k_d^2 k_T R \omega_0^{a-1}}{T_m};\ m_1 = \frac{1}{T_m};\ m_0 = -\frac{1}{T_m}. \tag{6}$$

The study drive's dynamic in a relative units allows us to consider its state variable w, control signal v, and idle torque t_0 in range $[0, 1]$ instead of their real values. It is clear that such approach gives us the possibility to make dynamic representation and comparison more clear.

It is necessary to say that the values of drive's parameters is not exactly known or they can change during the operation time because of heating, supplier's voltage variations and other environmental effects. We take into account possible parameters' variations by considering intervals of their possible values. In the mathematical way this assumption can be taking into account by following intervals

$$\mathbf{T_m} = [T_{m\ low}, T_{m\ up}];\ \mathbf{k_d} = [k_{d\ low}, k_{d\ up}];\ \mathbf{k_T} = [k_{T\ low}, k_{T\ up}];\ \mathbf{R} = [R_{low}, R_{up}]. \tag{7}$$

The usage of intervals (7) allows us to rewrite factors (6) in the interval compact

$$\mathbf{b_1} = -\frac{1}{\mathbf{T_m}};\ \mathbf{b_{1a}} = -\frac{\mathbf{k_d}^2\mathbf{k_T}\mathbf{R}\omega_0^{\mathbf{a}-1}}{\mathbf{T_m}};\ \mathbf{m_1} = \frac{1}{\mathbf{T_m}};\ \mathbf{m_0} = -\frac{1}{\mathbf{T_m}} \tag{8}$$

and extended

$$\begin{gathered}\mathbf{b_1} = \mathbf{m_0} = \left[-\frac{1}{T_{m\ min}}, -\frac{1}{T_{m\ max}}\right];\ \mathbf{m_1} = \left[\frac{1}{T_{m\ max}}, \frac{1}{T_{m\ min}}\right];\\ \mathbf{b_{1a}} = \left[-\frac{{k_{d\ max}}^2 k_{T\ max} R_{max}\omega_0^{a_{max}-1}}{T_{m\ min}}, -\frac{{k_{d\ min}}^2 k_{T\ min} R_{min}\omega_0^{a_{min}-1}}{T_{m\ max}}\right]\end{gathered} \tag{9}$$

forms.

Now we design the interval piecewise linear model for the uncertain plant's nonlinearity (figure 1). Here we define upper piecewise linear boundary for the nonlinear torque with factors $a = 1.5$ and lower one for the case when $a = 2.5$. In this and others figures we show results of our studies for dimensionless electric drive model. In this case we assume that 1 in figure means maximal possible value of electric drive state variables.

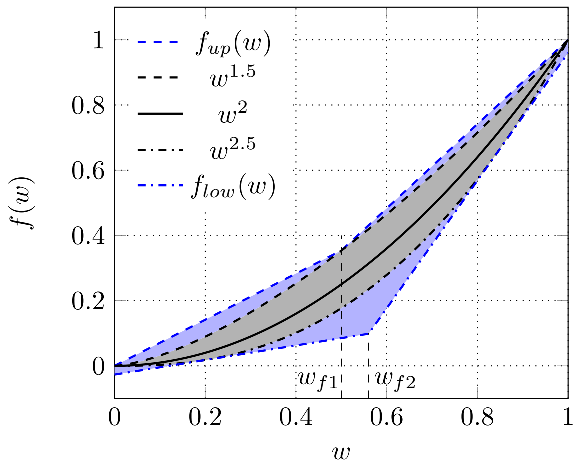

Figure 1. Domain of the nonlinearities possible values.

The solution of minimization problem for piecewise linear bounded area in (figure 1)

$$I = \sum_{i=1}^{n}\int_0^{y_{fi}} (f(y)^2_{iup} - f(y)^2)dt + \sum_{i=1}^{m}\int_0^{y_{fi}} (f(y)^2 - f(y)^2_{ilow})dt \rightarrow min \tag{10}$$

for functions

$$f_1(w) = w^{1.5};\ f_2(w) = w^{2.5} \tag{11}$$

gives us the possibility to define fracture points $w_{f1} = 0.5$ and $w_{f2} = 0.56$ in upper and lower boundaries and appropriate piecewise linear functions are determined in such a way

$$f_{up}(w) = \begin{cases} 0.701w & if \quad 0 \leq w \leq 0.5; \\ 1.293w - 0.293 & if \quad 0.5 < w \leq 1, \end{cases}$$
$$f_{low}(w) = \begin{cases} 0.223w - 0.027 & if \quad 0 \leq w \leq 0.56; \\ 1.959w - 1.0 & if \quad 0.56 < w \leq 1. \end{cases} \tag{12}$$

Function (12) can be rewritten in the interval form

$$\mathbf{f}(w) = \begin{cases} \mathbf{k_{11}}w + \mathbf{k_{01}} & if \quad w \in \mathbf{w_{f1}}; \\ \mathbf{k_{12}}w + \mathbf{k_{02}} & if \quad w \in \mathbf{w_{f12}}; \\ \mathbf{k_{13}}w + \mathbf{k_{03}} & if \quad w \in \mathbf{w_{f2}}, \end{cases} \tag{13}$$

if one assumes following intervals for its factors

$$\begin{aligned} &\mathbf{k_{11}} = [0.701, 0.223];\ \mathbf{k_{12}} = [1.293, 0.223];\ \mathbf{k_{13}} = [1.293, 1.959]; \\ &\mathbf{k_{01}} = [0.0, -0.027];\ \mathbf{k_{02}} = [-0.293, -0.027];\ \mathbf{k_{03}} = [-0.293, -1.0]; \\ &\mathbf{w_{f1}} = [0, w_{f1}];\ \mathbf{w_{f12}} = [w_{f1}, w_{f2}];\ \mathbf{w_{f2}} = [w_{f2}, 1]. \end{aligned} \tag{14}$$

Substitution (13) into (5) allows us to write down interval model for the considered electric drive

$$\dot{\mathbf{w}} = \begin{cases} (\mathbf{b_1} + \mathbf{k_{11}}\mathbf{b_{1a}})\mathbf{w} + \mathbf{m_1}v + \mathbf{m_0}t_0 + \mathbf{k_{01}}\mathbf{b_{1a}} & if \quad w \in \mathbf{w_{f1}}; \\ (\mathbf{b_1} + \mathbf{k_{12}}\mathbf{b_{1a}})\mathbf{w} + \mathbf{m_1}v + \mathbf{m_0}t_0 + \mathbf{k_{02}}\mathbf{b_{1a}} & if \quad w \in \mathbf{w_{f12}}; \\ (\mathbf{b_1} + \mathbf{k_{13}}\mathbf{b_{1a}})\mathbf{w} + \mathbf{m_1}v + \mathbf{m_0}t_0 + \mathbf{k_{03}}\mathbf{b_{1a}} & if \quad w \in \mathbf{w_{f2}}. \end{cases} \tag{15}$$

We call (15) as piecewise linear interval model of electric drive with ventilator load.

3. Interval model in the operator form

Let us assume that before control signal is supplied to the electric drive, it has already operates with speed near 5% from idle speed because of environment affects. This fact defines non-zero initial condition

$$W(0) = 0.05, \tag{16}$$

which makes it possible to rewrite (15) into the operator form

$$\begin{cases} s\mathbf{W}(s) - sw(0) = \mathbf{a_{11}}\mathbf{W}(s) + \mathbf{m_1}V(s) + \mathbf{m_0}T_0(s) + \mathbf{a_{01}} & if \quad w \in \mathbf{w_{f1}} and sw > 0; \\ s\mathbf{W}(s) - sw_{f1}(0) = \mathbf{a_{11}}\mathbf{W}(s) + \mathbf{m_1}V(s) + \mathbf{m_0}T_0(s) + \mathbf{a_{01}} & if \quad w \in \mathbf{w_{f1}} \ and \ sw < 0; \\ s\mathbf{W}(s) - sw_{f1}(0) = \mathbf{a_{12}}\mathbf{W}(s) + \mathbf{m_1}V(s) + \mathbf{m_0}T_0(s) + \mathbf{a_{02}} & if \quad w \in \mathbf{w_{f12}} \ and \ sw > 0; \\ s\mathbf{W}(s) - sw_{f2}(0) = \mathbf{a_{12}}\mathbf{W}(s) + \mathbf{m_1}V(s) + \mathbf{m_0}T_0(s) + \mathbf{a_{02}} & if \quad w \in \mathbf{w_{f12}} \ and \ sw < 0; \\ s\mathbf{W}(s) - sw_{f2}(0) = \mathbf{a_{13}}\mathbf{W}(s) + \mathbf{m_1}V(s) + \mathbf{m_0}T_0(s) + \mathbf{a_{03}} & if \quad w \in \mathbf{w_{f2}} \ and \ sw > 0; \\ s\mathbf{W}(s) - sw_0 = \mathbf{a_{13}}\mathbf{W}(s) + \mathbf{m_1}V(s) + \mathbf{m_0}T_0(s) + \mathbf{a_{03}} & if \quad w \in \mathbf{w_{f2}} \ and \ sw < 0; \end{cases} \tag{17}$$

here

$$\begin{aligned} &\mathbf{a_{11}} = \mathbf{b_1} + \mathbf{k_{11}}\mathbf{b_{1a}};\ \mathbf{a_{01}} = \mathbf{k_{01}}\mathbf{b_{1a}}; \\ &\mathbf{a_{12}} = \mathbf{b_1} + \mathbf{k_{12}}\mathbf{b_{1a}};\ \mathbf{a_{02}} = \mathbf{k_{02}}\mathbf{b_{1a}}; \\ &\mathbf{a_{13}} = \mathbf{b_1} + \mathbf{k_{13}}\mathbf{b_{1a}};\ \mathbf{a_{03}} = \mathbf{k_{03}}\mathbf{b_{1a}}; \end{aligned} \tag{18}$$

Applying trivial algebraic transformations for (17) makes it possible to rewrite (17) into matrix form

$$\mathbf{W}(s) = \mathbf{K}(s) \cdot \mathbf{X}(s) \tag{19}$$

by using piecewise interval matrix transfer function

$$\mathbf{K}(s)=\begin{cases}\begin{pmatrix}\frac{\mathbf{m_1}}{s-\mathbf{a_{11}}} & \frac{\mathbf{m_0}}{s-\mathbf{a_{11}}} & \frac{sw(0)+\mathbf{a_{01}}}{s-\mathbf{a_{11}}}\end{pmatrix} & if \quad w\in\mathbf{w_{f1}}\ and\ sw>0;\\ \begin{pmatrix}\frac{\mathbf{m_1}}{s-\mathbf{a_{11}}} & \frac{\mathbf{m_0}}{s-\mathbf{a_{11}}} & \frac{sw_{f1}(0)+\mathbf{a_{01}}}{s-\mathbf{a_{11}}}\end{pmatrix} & if \quad w\in\mathbf{w_{f1}}\ and\ sw<0;\\ \begin{pmatrix}\frac{\mathbf{m_1}}{s-\mathbf{a_{12}}} & \frac{\mathbf{m_0}}{s-\mathbf{a_{12}}} & \frac{sw_{f1}(0)+\mathbf{a_{02}}}{s-\mathbf{a_{12}}}\end{pmatrix} & if \quad w\in\mathbf{w_{f12}}\ and\ sw>0;\\ \begin{pmatrix}\frac{\mathbf{m_1}}{s-\mathbf{a_{12}}} & \frac{\mathbf{m_0}}{s-\mathbf{a_{12}}} & \frac{sw_{f2}(0)+\mathbf{a_{02}}}{s-\mathbf{a_{12}}}\end{pmatrix} & if \quad w\in\mathbf{w_{f12}}\ and\ sw<0;\\ \begin{pmatrix}\frac{\mathbf{m_1}}{s-\mathbf{a_{13}}} & \frac{\mathbf{m_0}}{s-\mathbf{a_{13}}} & \frac{sw_{f2}(0)+\mathbf{a_{03}}}{s-\mathbf{a_{13}}}\end{pmatrix} & if \quad w\in\mathbf{w_{f2}}\ and\ sw>0;\\ \begin{pmatrix}\frac{\mathbf{m_1}}{s-\mathbf{a_{13}}} & \frac{\mathbf{m_0}}{s-\mathbf{a_{13}}} & \frac{sw_0+\mathbf{a_{03}}}{s-\mathbf{a_{13}}}\end{pmatrix} & if \quad w\in\mathbf{w_{f2}}\ and\ sw<0;\end{cases} \tag{20}$$

and the generalized inputs vector

$$\mathbf{X}(s)=\begin{pmatrix} V(s) & T_0(s) & 1(s)\end{pmatrix}. \tag{21}$$

Results of numerical solution of (19) are shown in figure 2. Also, to compare both interval and exact solutions, we show in this figure results of numerical solution of (5) with conventional value of a factor.

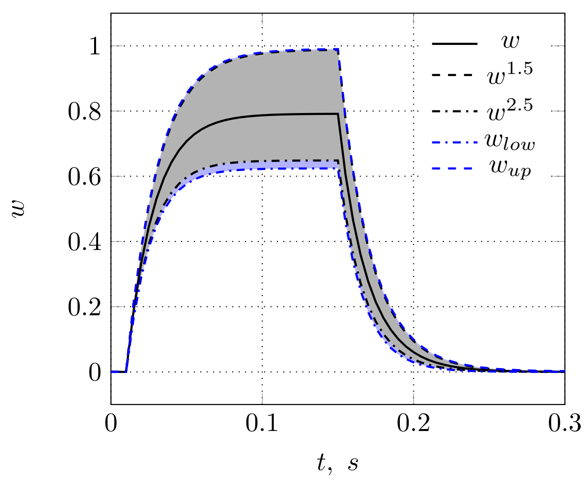

Figure 2. Simulation results of electric drive start, steady state, and stop.

Analysis of obtained simulation results shows that exact solution is localized in the area which is bounded by interval solutions for upper and lower boundaries. If one analyzes figure 2, he finds what the main uncertainty in the model is made by uncertainty of electric drive's parameters and factor a values (grey area in figure 2) and only minor one is caused by using piecewise linear boundaries (blue area in figure 2).

4. Interval piecewise controller design

The use of above-shown approach to define controller transfer function requires to determine the desired transfer function and transfer function of feedback channel. Here we assume that feedback channel has non-inertial dynamic. Also, we think that asymptotic motions are energy-efficient ones and that is why define the desired transfer function of closed-loop system in such a way

$$\Phi^*(s) = \frac{k^*}{T^*s + 1}, \tag{22}$$

where k^* is a desired system gain and T^* is its time constant.

We use (22) and (20) to define controller interval transfer function as follows

$$\mathbf{K_c}(s) = \begin{cases} \left(\frac{k^*(s - \mathbf{a_{11}})}{\mathbf{m_1}(T^*s - \mathbf{k_f}k^* + 1)} \quad -\frac{\mathbf{m_0}}{\mathbf{m_1}} \quad -\frac{sw(0) + \mathbf{a_{01}}}{\mathbf{m_1}} \right) & if \quad \begin{matrix} w \in \mathbf{w_{f1}} \\ and\ sw > 0; \end{matrix} \\ \left(\frac{k^*(s - \mathbf{a_{11}})}{\mathbf{m_1}(T^*s - \mathbf{k_f}k^* + 1)} \quad -\frac{\mathbf{m_0}}{\mathbf{m_1}} \quad -\frac{sw_{f1}(0) + \mathbf{a_{01}}}{\mathbf{m_1}} \right) & if \quad \begin{matrix} w \in \mathbf{w_{f1}} \\ and\ sw < 0; \end{matrix} \\ \left(\frac{k^*(s - \mathbf{a_{12}})}{\mathbf{m_1}(T^*s - \mathbf{k_f}k^* + 1)} \quad -\frac{\mathbf{m_0}}{\mathbf{m_1}} \quad -\frac{sw_{f1}(0) + \mathbf{a_{02}}}{\mathbf{m_1}} \right) & if \quad \begin{matrix} w \in \mathbf{w_{f12}} \\ and\ sw > 0; \end{matrix} \\ \left(\frac{k^*(s - \mathbf{a_{12}})}{\mathbf{m_1}(T^*s - \mathbf{k_f}k^* + 1)} \quad -\frac{\mathbf{m_0}}{\mathbf{m_1}} \quad -\frac{sw_{f2}(0) + \mathbf{a_{02}}}{\mathbf{m_1}} \right) & if \quad \begin{matrix} w \in \mathbf{w_{f12}} \\ and\ sw < 0; \end{matrix} \\ \left(\frac{k^*(s - \mathbf{a_{13}})}{\mathbf{m_1}(T^*s - \mathbf{k_f}k^* + 1)} \quad -\frac{\mathbf{m_0}}{\mathbf{m_1}} \quad -\frac{sw_{f2}(0) + \mathbf{a_{03}}}{\mathbf{m_1}} \right) & if \quad \begin{matrix} w \in \mathbf{w_{f2}} \\ and\ sw > 0; \end{matrix} \\ \left(\frac{k^*(s - \mathbf{a_{13}})}{\mathbf{m_1}(T^*s - \mathbf{k_f}k^* + 1)} \quad -\frac{\mathbf{m_0}}{\mathbf{m_1}} \quad -\frac{sw_0 + \mathbf{a_{03}}}{\mathbf{m_1}} \right) & if \quad \begin{matrix} w \in \mathbf{w_{f2}} \\ and\ sw < 0. \end{matrix} \end{cases} \tag{23}$$

One can use defined in such a way the generalized interval controller transfer function to write down interval control law for the considered electric drive

$$\mathbf{V(s)} = \mathbf{K_c}(s) \cdot \mathbf{X_c}(s), \tag{24}$$

here $\mathbf{X_c}(s)$ is a vector of closed-loop system's inputs

$$\mathbf{X_c}(s) = \begin{pmatrix} W^*(s) - W(s) & T_0(s) & 1(s) \end{pmatrix}. \tag{25}$$

Analysis of (25) shows that to control the considered electric drive it is necessary to have informations about control error, idle torque, and drive's initiial conditions which are caused by its variable structure.

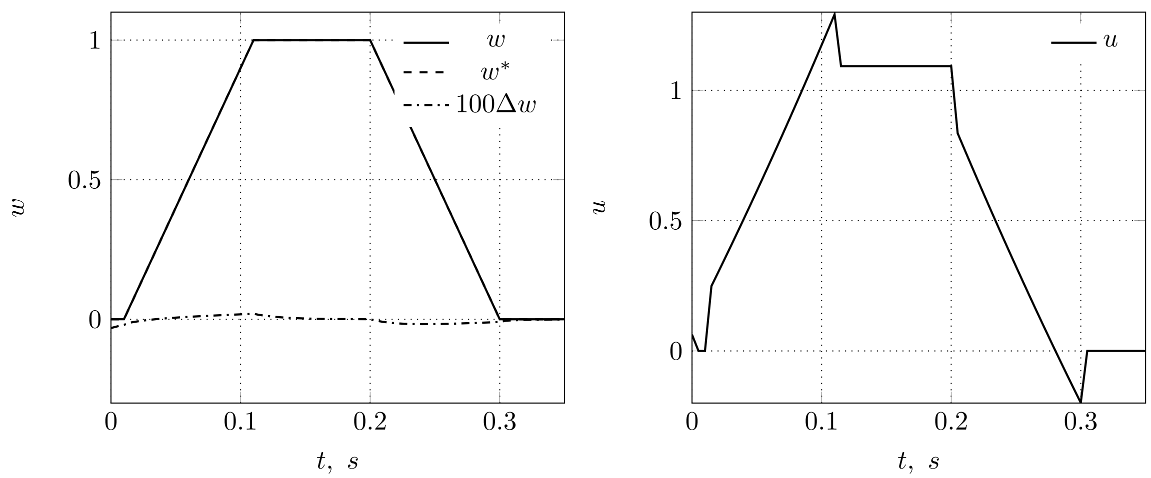

Figure 3. Simulation results for the designed closed-loop control system.

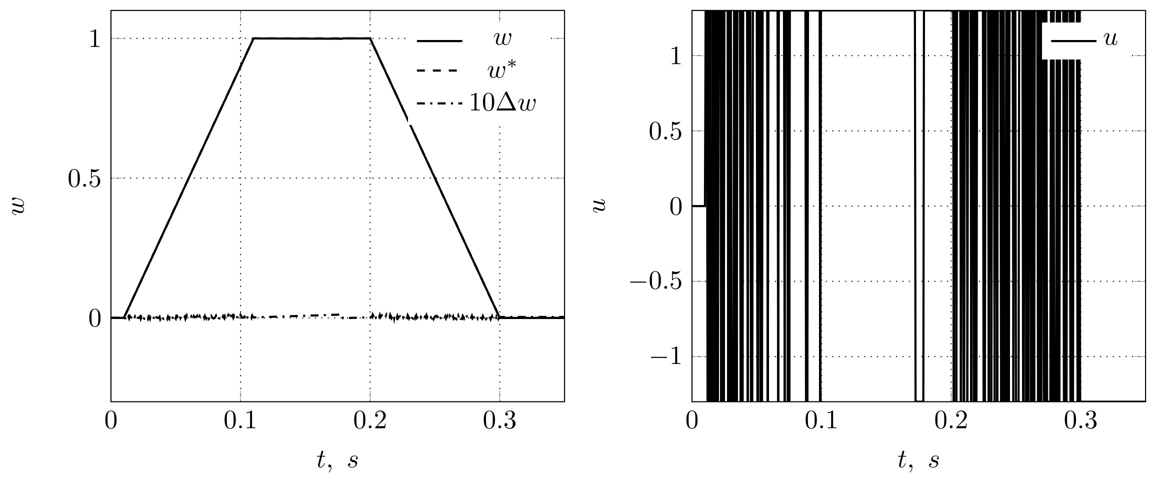

Figure 4. Simulation results for the sliding mode control system.

Control law (24) defines lower

$$V_{low}(s)=\begin{cases} \dfrac{k^*(s-a_{11up})}{m_{1up}(T^*s-k_{flow}k^*+1)}(W^*(s)-W(s))- \\ \quad -\dfrac{m_{0up}}{m_{1low}}T_0(s)-\dfrac{sw(0)+a_{01up}}{m_{1low}}\cdot 1(s) & if \quad w\in \mathbf{w_{f1}} \text{ } and\ sw>0; \\ \dfrac{k^*(s-a_{11up})}{m_{1up}(T^*s-k_{flow}k^*+1)}(W^*(s)-W(s))- \\ \quad -\dfrac{m_{0up}}{m_{1low}}T_0(s)-\dfrac{sw_{f1}+a_{01up}}{m_{1low}}\cdot 1(s) & if \quad w\in \mathbf{w_{f1}} \text{ } and\ sw<0; \\ \dfrac{k^*(s-a_{12up})}{m_{1up}(T^*s-k_{flow}k^*+1)}(W^*(s)-W(s))- \\ \quad -\dfrac{m_{0up}}{m_{1low}}T_0(s)-\dfrac{sw_{f1}+a_{02up}}{m_{1low}}\cdot 1(s) & if \quad w\in \mathbf{w_{f12}} \text{ } and\ sw>0; \\ \dfrac{k^*(s-a_{12up})}{m_{1up}(T^*s-k_{flow}k^*+1)}(W^*(s)-W(s))- \\ \quad -\dfrac{m_{0up}}{m_{1low}}T_0(s)-\dfrac{sw_{f2}+a_{02up}}{m_{1low}}\cdot 1(s) & if \quad w\in \mathbf{w_{f12}} \text{ } and\ sw<0; \\ \dfrac{k^*(s-a_{13up})}{m_{1up}(T^*s-k_{flow}k^*+1)}(W^*(s)-W(s))- \\ \quad -\dfrac{m_{0up}}{m_{1low}}T_0(s)-\dfrac{sw_{f2}+a_{03up}}{m_{1low}}\cdot 1(s) & if \quad w\in \mathbf{w_{f2}} \text{ } and\ sw>0; \\ \dfrac{k^*(s-a_{13up})}{m_{1up}(T^*s-k_{flow}k^*+1)}(W^*(s)-W(s))- \\ \quad -\dfrac{m_{0up}}{m_{1low}}T_0(s)-\dfrac{sw_0+a_{03up}}{m_{1low}}\cdot 1(s) & if \quad w\in \mathbf{w_{f2}} \text{ } and\ sw<0. \end{cases} \tag{26}$$

and upper

$$V_{up}(s) = \begin{cases} \dfrac{k^*(s-a_{11low})}{m_{1low}(T^*s-k_{fup}k^*+1)}(W^*(s)-W(s))- & \\ -\dfrac{m_{0low}}{m_{1up}}T_0(s)-\dfrac{sw(0)+a_{01low}}{m_{1up}}\cdot 1(s) & if \quad \begin{matrix} w\in \mathbf{w_{f1}} \\ and\ sw>0; \end{matrix} \\ \dfrac{k^*(s-a_{11low})}{m_{1low}(T^*s-k_{fup}k^*+1)}(W^*(s)-W(s))- & \\ -\dfrac{m_{0low}}{m_{1up}}T_0(s)-\dfrac{sw_{f1}+a_{01low}}{m_{1up}}\cdot 1(s) & if \quad \begin{matrix} w\in \mathbf{w_{f1}} \\ and\ sw<0; \end{matrix} \\ \dfrac{k^*(s-a_{12low})}{m_{1low}(T^*s-k_{fup}k^*+1)}(W^*(s)-W(s))- & \\ -\dfrac{m_{0low}}{m_{1up}}T_0(s)-\dfrac{sw_{f1}+a_{02low}}{m_{1up}}\cdot 1(s) & if \quad \begin{matrix} w\in \mathbf{w_{f12}} \\ and\ sw>0; \end{matrix} \\ \dfrac{k^*(s-a_{12low})}{m_{1low}(T^*s-k_{fup}k^*+1)}(W^*(s)-W(s))- & \\ -\dfrac{m_{0low}}{m_{1up}}T_0(s)-\dfrac{sw_{f2}+a_{02low}}{m_{1up}}\cdot 1(s) & if \quad \begin{matrix} w\in \mathbf{w_{f12}} \\ and\ sw<0; \end{matrix} \\ \dfrac{k^*(s-a_{13low})}{m_{1low}(T^*s-k_{fup}k^*+1)}(W^*(s)-W(s))- & \\ -\dfrac{m_{0low}}{m_{1up}}T_0(s)-\dfrac{sw_{f2}+a_{03low}}{m_{1up}}\cdot 1(s) & if \quad \begin{matrix} w\in \mathbf{w_{f2}} \\ and\ sw>0; \end{matrix} \\ \dfrac{k^*(s-a_{13low})}{m_{1low}(T^*s-k_{fup}k^*+1)}(W^*(s)-W(s))- & \\ -\dfrac{m_{0low}}{m_{1up}}T_0(s)-\dfrac{sw_0+a_{03low}}{m_{1up}}\cdot 1(s) & if \quad \begin{matrix} w\in \mathbf{w_{f2}} \\ and\ sw<0. \end{matrix} \end{cases} \tag{27}$$

boundary of control signal, which should be supplied to the considered electric drive.

Simulation results of the designed control system are shown in figure 3.

Analysis of the above-given simulation results shows that designed system has zero control error in the steady state and near zero dynamical error while drive starts and stops. Voltage which is supplied to drive is continuous and physicaly-implemented one.

Now we show the benifits of our system from energy viewpoint by comparing it with a classical sliding mode control system which allows to get zero control error in system's dynamic and steady state.

We consider closed-loop control system with controller which implements folowing control law

$$U(s) = U_{max}\cdot sign(W^*(s)-W(s)). \tag{28}$$

As one can see the use of sliding mode controller allows drammaticaly reduce control error. At the same time sliding mode control system consumes much more energy than other control systems (figure 5). As an indicator of system energy efficiency we use following integral which shows all control energy

$$I = \int_0^\infty u^2 dt \tag{29}$$

Comparison of graphics in figure 5 proves the benifit of our approach because of its allows to reduce energy consuming near three times due to using continuous control signal which contrary to discontinuous sliding mode control can have zero value.

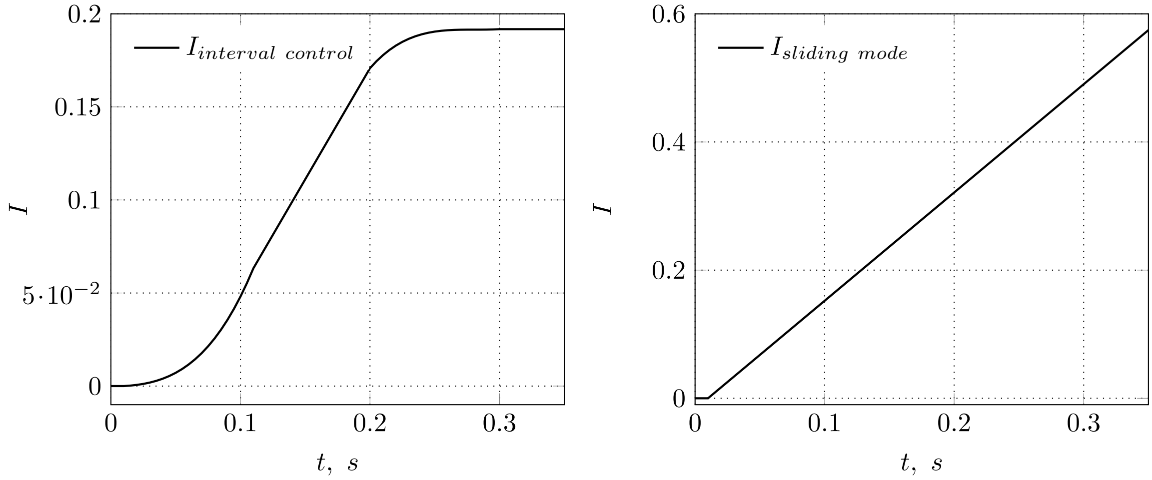

Figure 5. Energy characteristics of studied systems.

5. Conclusion

The use of inerval methods to define dynamical systems motions allows us to take into account possible uncertainies and nonlinearities of the considered plant and gives possibility to write down differential equations in piecewise linear form. These equations allows to define the generalized transfer function which for the nonlinear uncertain plant can be considered as piecewise matrix anisotropic differential operator. The use of this operator make it possible to design variable-structure controller which can be implemented in both anaolg and digital ways. The control system with such a controller has performance and control error similar to sliding mode system but consumes three times less energy what should be useful to design energy-eficient industrial processes based on the turbomachinery usage.

Since a lot of industrial processes and equipments are defined by the second and third order differential equations, we see future development of our approach in considering high order dynamical system and design optimal energy-efficient controllers for them.

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Concession as a tool for improving the budget and tax incentives for investment attractiveness of the tourist complex in Ukraine

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Concession as a tool for improving the budget and tax incentives for investment attractiveness of the tourist complex in Ukraine

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Abstract. The argumentation of the use of concession of historical and architectural objects in Ukraine as a tool for improving the budget and tax incentives for investment attractiveness of the tourist complex has been carried out. A scientific approach to budgetary and tax incentives for investment attractiveness of tourist facilities has been formed using an optimization model for calculating concession payments, which ensures the flexibility of incentives, takes into account the interests of investors, based on indicators for assessing the effectiveness of an investment project with a simultaneous focus on maximizing budget revenues. It is substantiated that the budgetary and tax incentives for investment attractiveness of tourist complexes through the introduction of public-private partnership in the form of a concession of historical and architectural objects will allow private business to invest in attractive tourist sites and ensure higher profitability of the hotel and restaurant business, since the interests of the investor are taken into account, and will also reduce budget expenditures and increase tax revenues to the budgets from servicing tourist flows.

1. Introduction

Today, the problem of preserving the historical and architectural component of the tourism industry [1, 2] has arisen quite sharply in Ukraine. Since, having a rich tourist potential, the Ukrainian economy not only does not use it to the full, while not maintaining revenues from tourist flows, moreover, objects of historical and architectural heritage every day, waiting for financing and repairs, are destroyed and lose tourist attractiveness, and often simply disappear from the tourist map of Ukraine [3, 4].

Foreign and domestic practice has proved that the most effective form of protection of historical cities is the allocation of areas with a special regime of development and reconstruction on their territory, the organization of reserves. In Ukraine, the transition to comprehensive protection of the cultural heritage of cities began in 1975 with a historical and cultural reserve that covered the historical center of the city of Lviv. Then similar reserves were created in Kamianets-Podilskyi (1977), Chernihiv and Novhorod-Siverskyi (1978), Pereiaslav-Khmelnytskyi (1979). Ostrozi (1981), Lutsk (1985), Putivli (1986), Kerch and Kyiv (1987), Bakhchysarai (1990), Baturyn and Dubna (1992), Hlukhiv, Zbarazhi, Halychy, Odesa, Korsun-

Shevchenkivskyi (1994), etc. In total, out of 38 reserves of the historical and cultural profile, 18 areassociated with the protection of heritage in cities.

All reserves should be managed by a single state body for the protection of cultural heritage. In the meantime, the next management system has been formed. The Ministry of Culture and Information Policy of Ukraine manages seven nature reserves, the State Committee for Urban Development manages four. The National Academy of Sciences – only one. The remaining reserves are subordinate to regional or district administrations.

Currently, the state program for the development of historical and cultural reserves of Ukraine is being developed, which would identify the whole range of problems – from the criteria for assessing heritage to the principles of financing activities and insurance of risks arising in this case, in particular:

1) reservation of leading historical and cultural complexes for the next organization of reserves.
2) creation of new reserves in the system of the unified state body for the protection of historical and cultural heritage;
3) financing of reserves in a separate line in the state budget, as has already been done for biosphere and nature reserves, as well as national parks;
4) development of master plans for development and comprehensive regeneration programs for all reserves.

Despite all the current difficulties and uncertainty of the legislative framework, reserves now and in the future remain the optimal form of comprehensive protection of the historical and cultural environment.

The search for ways to solve the outlined problem, as the practice of managing tourist facilities in Ukraine shows, is rather limited. On the one hand, most of the objects are state property and belong to monuments of national and local importance, but on the other hand, it is the protection of architectural authenticity that makes the process of their restoration and reconstruction extremely difficult. Budget financing is usually aimed at preserving these objects from further destruction, and not always successful. And the access of a private investor to historical buildings is limited by the lack of commercial motives and the complexity of the mechanism of investing in state-owned objects [5].

Analysis of possible sources of investment in tourist facilities showed that the most optimal is the development of public-private partnership (PPP) in the tourism sector, namely the concession agreement, which is popular both in Ukraine and abroad. A public-private partnership is a long-term cooperation between public and private organizations aimed at fulfilling public responsibilities and allocating risks, rewards and responsibilities to the partner (government or contractor) that is best able to manage them [6]. Public-private partnerships usually include various contractual agreements, which may differ depending on the sector they relate to and the national legislation of each country. Among the various financial arrangements, a concession is usually considered to be a "design-build-finance-operate-maintain" PPP instrument [7]. In this case, the contractor designs, builds, finances and operates the cultural heritage site. Given that governments typically use different procurement and contracts for each of the above-mentioned stages of the process, concessions allow contractors to be more involved not only in decision-making but also in the subsequent management of cultural heritage sites. Concessions are a particularly attractive way to implement projects in the public interest when state or local authorities need to mobilize private capital and know-how to supplement limited public resources. They are the basis of a significant share of EU economic activity and are especially common in network industries and for the provision of services of general economic interest [8]. However, almost all concession projects in Ukraine are insignificant and are implemented in the field of housing and communal services, construction of roads and seaport facilities of the seaport industry.

Thus, the purpose of the study is to deepen the theoretical and methodological provisions and develop practical recommendations for fiscal stimulation of the investment attractiveness of the tourism complex by forming an effective public-private partnership in the field of preservation of historical and architectural objects. The objectives of the study include:

- analysis of foreign and domestic experience in the field of concession in general and tourism facilities in particular;
- establishing the conditions necessary for the transfer of cultural heritage sites into concession;
- analysis of the advantages and disadvantages of concession of historical and architectural objects; determination of the optimal rate of concession payment through the optimization problem of mathematical programming;
- substantiation of the elements of the optimization model for determining concession payments;
- calculation of the budgetary and tax effect of the implementation of the optimization model for determining concession payments.

2. Literature review

It should be noted that the vast majority of scientists believe that the development of public-private partnerships, in particular the concession agreement, is a particularly attractive way to implement various projects in the public interest, when state or local authorities need to mobilize private capital to supplement limited public resources. Thus, Carpintero analyzes the competitive advantages enjoyed by Spanish companies in the international toll road industry and how profitable such concessions are [9]. Bogunović and Kukurin substantiated the positive impact of land concessions on the camping business in the coastal areas of Croatia [10]. Fujiwara reflected the benefits of public-private partnerships in Japan's sustainable public sewage industry [11]. Łapniewska substantiates the advantages of concession on the Berlin electricity grid (the largest in Germany) [12]. Khmurova et al. substantiate the strategy for the development of public-private partnership in the context of global changes [13].

The use of such a tool as a concession in the tourism sector is widely used in many countries around the world. Therefore, Pizzanelli compares the legal aspects of national and European law in the process of regulating state maritime concessions for tourist and recreational use and procedures related to their purpose [14].

Dinica substantiates the use of concessions for tourism business in protected areas, including national parks in New Zealand, with special reference to their financial and in-kind contributions to conservation work [15].

Rodrigues and Abrucio [16], Brumatti and Rozendo [8] consider partnerships and concessions as an alternative for tourism management, a priority for the federal government and for the development of tourism in Brazilian parks, as well as the creation of institutional arrangements with the private sector through concessions to provide tourism alternatives and recreational services.

Wyman et al. [17] analyzed the best practices of tourism concessions through private sector partnerships in tourism in 22 countries. They identified environmental and empowerment commitments and social commitments as the strengths of the best practices of tourism concessions, with these components being most represented in Colombia, Costa Rica, Botswana and South Africa. The analysis of government documents and case studies showed that the biggest gaps in best practices relate to qualification requirements for concessionaires, legal and financial obligations. Canada, New Zealand, Costa Rica, and Botswana demonstrated a higher representation of agreements with these components.

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At the same time, despite the significant revenue potential of managing protected areas through private tourism concessions, there are also situations where it is necessary to refrain from approving concessions. Paying for a concession may not be an effective option for some sites, especially if demand for services is limited. In some cases, demand may exist, but the potential concessionaire may not be sufficiently capitalized, interested, or willing to take financial risks. Examples from South Africa and Colombia confirm these problems [18].

It should be noted that there are a number of works that criticize the use of concessions, but such criticism mainly concerns the ability of local authorities to transparently and fairly manage the process of obtaining economic and social benefits, as well as achieving the main goal of protected areas – environmental protection [15, 17–19].

A strong point of concessions in the tourism sector is the support of environmentally responsible tourism practices. Thus, concession agreements increasingly include measures to minimize environmental impact. Depending on the type of concession activity, contracts may require management plans in areas such as waste disposal, infrastructure development, water use and management, and waste recycling measures [20].

The concession of cultural heritage occupies a special place in scientific research and the practice of applying public-private partnership agreements in many countries. Boniotti describes the useful role of research in investment analysis for concessions for Italian state-owned cultural heritage sites [21, 22]. The main examples of public-private partnerships in Italy include the wing of the Royal Villa in Monza, which is currently under concession to a private firm [23]; the 16th-century Villa del Bene, located in Dolce (Verona Province), is now managed by the Regional Directorate of Museums in cooperation with the local agency Pro Loco (local promotion agency). It has become a museum, educational center, contemporary art gallery, and a venue for conferences and weddings [24]; acquisition of the Castle of Pergine (Trento Province) by the CastelPergine Foundation through public underwriting [25].

Lee [26] focuses on the study of the impact of the private sector on the preservation of cultural heritage in China on the example of the Xinhepu Conservation Area in the old residential district of Yuexiu in Guangzhou [25].

Negussie explores the impact of neoliberal conventions and practices on institutional and ownership structures in cultural heritage management using the experience of Ireland and Sweden [27]. Hofmeister and Borchert put forward proposals for improving public-private partnerships in Switzerland [28].

It should be noted that the study of the issue of concession of tourist facilities in Ukraine is urgent, because if these processes are not activated in the coming years, then historical and architectural monuments will completely lose their investment attractiveness.

Returning to the analysis of the Law of Ukraine "On Concessions" [29], in the context of our study, we see that the objects that can be granted a concession include those that carry out activities in such areas of economic activity as the construction and operation of hotels, tourist complexes, campsites and other relevant objects of the tourism industry. According to the European Commission, concessionaires can, for example, build and operate motorways, provide airport services or operate water distribution networks, etc. [30].

The legislator is rather unclear on the issue of whether the concession object includes, for example: fortifications, castle complexes, towers and other architectural monuments. However, practice shows that they act as such objects, but not without a question from the public about the legality of such a concession agreement.

Thus, in 2010, the Lviv Regional State Administration for the first time in Ukrainian practice transferred two old emergency buildings to a concession for 49 years – a palace in Tartakiv (Sokal district) and the ruins of a castle in the Old Village (Pustomyty) district. The first monument was planned to be used as a cultural and recreational complex, and the second – as a platform for festivals and mass events. Despite the obligation to immediately carry out emergency work and bring the monuments to proper condition in a few years, so far none of the concessionaires even has ready design documentation [31]. Accordingly, during the years of inactivity of the concessionaires, the condition of the facilities deteriorated. To better understand the depth of the problem of concession agreements for castle tourism facilities, we will analyze the appeal of the head of the RSA to the Cabinet of Ministers of Ukraine with a request to allow the transfer of Pidhirtsi Castle to concession and grant the right to determine the concessionaire to the regional state administration. However, the draft resolution of the Cabinet of Ministers, according to which all the requests of the RSA were satisfied, was never signed. The initiatives of the concession regarding the Svirzh Castle (the initiative of the RSA in 2005) and the creation of a recreation complex on the site of the archaeological monument "Novobogoroditska Fortress" in Dnipro did not advance. The concession of the castle "Palanok" in Mukachevo was rejected by the decision of the Verkhovna Rada.

One of the problems that stands in the way of concession agreements is the uncertainty of ownership of objects, for example, Pidhirtsi Castle is absent from the General Register of State Property. Today, there are about 300 castles and about 5 thousand objects of defense architecture on the state register, while only 10%, according to experts, are in satisfactory condition [32]. And now, it is necessary to take into account that the priority restoration work is estimated at UAH 30-35 million in Svirzh Castle, and more than UAH 350 million in Pidhirtsi Castle.

Obviously, in the scale of tourist sites, only a small proportion of them have a chance to receive budget financing, and only after the stabilization of the situation in Ukraine. On the other hand, it is the presence of legislative conflicts that makes it impossible to attract private investment capital to restoration work. It is necessary to fill the legislative gap and add cultural heritage objects to the list of concession objects [33, p. 361].

Restoration of abandoned architectural monuments by private investors has a widespread and successful world practice. For example, the Chateau de Chantilly (France), owned by the Institut de France, under the terms of the concession is at the disposal of billionaire and philanthropist Karim Aga Khan IV and is open to tourist flows, international events and world championships. Similarly, the royal castle of Chenonceau has been privately owned by the Meunier family of entrepreneurs since the late nineteenth century, but is open to the public. The experience of Great Britain, the Czech Republic and neighboring Poland demonstrates that the concession and the leasing of monuments are perceived and popularized. There are dozens of Polish examples where the castle is simultaneously used as a hotel, museum, nature reserve and restaurant. In the Czech Republic, in addition to the concession of Konopiste, Karlštejn, Miroshnik, Sternberk castles, there is also an experience of selling castles into private hands, while historical palaces, fortresses and castles were sold at quite reasonable prices [34].

In turn, it is impossible to ignore the fact that in Ukraine for quite a long time they were extremely cautious about such concession agreements, fearing that the object of national importance would be privately owned. However, in conditions when since 2008, funding for castles from the state budget is practically not allocated, the question is not in whose ownership the object will be, but how to preserve it in general. Unfortunately, thecollapse of the tower at Chervonogorodsky Castle in 2013, the Gate Tower of the unique fortification and hydraulic structure of the Polish Gate (2009), the "New West Tower" on the territory of the Kamianets Historical and Architectural Reserve (2011) indicate that time is running out to find an investor. In addition, the Resolution of the Cabinet of Ministers of Ukraine "On the Effective Use of Public Funds" [35], which regulates the termination of the preparation of drafts of new state target programs or amendments to approved target programs that require additional funding from the state budget.

Although the concession issue is not limited to the concession permit, the question of how to make is limited to the concession permit, the question of how to make the facility attractive to the investor, while the investor has more incentives to invest in quick-recovery industries, with a higher rate of return, without fulfilling the obligation to the state and society to preserve the facility in good condition, its reconstruction in accordance with a whole set of rules and restoration requirements. The main problem is finding a concessionaire who will be willing to invest in the tourism industry in Ukraine [33, p. 362].

Article 6 of the Law of Ukraine "On Concessions" regulates that proposals on the list of specific objects of state ownership that can be granted in concession are made by the relevant central executive bodies. Approval of the object-by-object list is carried out by the Cabinet of Ministers of Ukraine [29]. It should be envisaged that the initiators of the preparation of concession proposals may include not only executive authorities, local self-government, but also investors (both residents and non-residents), which will allow them to independently initiate investment projects that interest them.

When transferring objects of cultural heritage to concession, it is necessary to comply with the following conditions [33, p. 362]:

- correct conduct of restoration work;
- work schedule and strict adherence to it;
- 70-80% of the use of the object for tourist (cultural) purposes and only partially for other functions, such as a hotel, museum, restaurant, gift shop, workshop, etc.;
- monuments of national importance must be accessible to visitors;
- compulsory insurance by the concessionaire of concession objects;
- granting concession payments privileges, including in the form of installments, deferrals, full or partial exemption from concession payments for a certain period of time to concessionaires of unprofitable and low-profitable concession facilities of social importance;
- the concessionaire may provide in the contract for the provision of subsidies, compensations and benefits, but only within the limits and in accordance with the procedure provided for by law;
- it is mandatory to carry out entrepreneurial activities on the basis of the operation of the concession facility (not to use the castle as an example for living);
- create jobs and conclude employment contracts, as a rule, with citizens of Ukraine;
- to use technologies, materials, and equipment of domestic production at the concession object, unless otherwise provided for by the terms of the agreement; to keep the concession object in proper technical condition;
- to transfer the concession object in proper technical condition to the concessor under the conditions of the agreement after the expiry of the concession agreement;
- providing the concessionaire with a land plot for the implementation of the relevant project.

The Law of Ukraine "On Concessions" actually does not provide benefits for the investor, according to which the concessionaire pays duty, VAT and excise tax when importing tangible assets under a concession agreement on a general basis. In addition, regardless of the consequences of economic activity, the concessionaire must pay a concession payment to the budget. Given this, both Ukrainian and foreign investors have no incentives to invest in infrastructure facilities. One of the tasks of forming investment attractiveness should be to ensure the flexibility of tax policy. So far, analyzing the legislation, it is quite difficult to name the signs of the attractiveness of the Ukrainian concession and distinguish its sectoral aspects. Despite this, the development and improvement of relations between business entities and the state, based on concession principles, is an important element of the approval of truly market methods of organizing the national economy. In addition, such aspects of tax policy in Ukraine regarding concession activities contradict the essence of the concession as a special business regime that establishes incentives for business entities [29]. It should be noted that the procedure for determining concession facilities, as well as the conditions for granting subsidies, compensations and benefits are established by the Cabinet of Ministers of Ukraine, but this significantly complicates the procedure, especially for small local tourist facilities. Therefore, it would be advisable to provide for the possibility of establishing the budget and tax incentives within the powers of local self-government bodies. Ukraine should also study the experience of collecting concession payments from countries where concession facilities are exempt from taxes. For example, Germany and France. It is necessary to think about certain preferences for taxpayers; alternatively, it is necessary to provide for the possibility of state aid. For example, in France, state grants for conservation and restoration of monuments are practiced, even if they are privately owned. But at the same time, the status of the monument and the accessibility mode are very clearly prescribed [32].

Returning to the cost of reconstruction of historical heritage sites, in compliance with all restoration requirements, the concession of tourist facilities requires significantly more investment resources than investment in other industries.

Therefore, preferences in concession activities should be sectoral in nature and accordingly increase the tools of benefits and incentives in accordance with the complexity of the investment process and the volume of investment.

Let us consider in more detail the concession of historical and architectural objects, and its advantages in comparison with other forms of management. However, along with the advantages, the concession also has a number of disadvantages that must be taken into account when looking for potential investors.

A distinctive feature of the concession in tourism is that the state, as one of the parties to the concession, has a monopoly on tourist resources (castles, museums, historical and architectural reserves, estates, defense structures, etc.). The most optimal type of concession agreement for tourist facilities, in our opinion, is: ROT – "Rehabilitate – Operate– Transfer". This scheme is similar to BOT – "Build – Operate – Transfer", only instead of the building of a new facility, the reconstruction of the existing one is provided [36, p. 42].

Thus, the concessionaire carries out the reconstruction of the historical and architectural object, and then operates it within the established period, after which the object is transferred to the state. Typically, BOT concession schemes are used during the construction of highways, pipelines, power plants, airports, tunnels, stadiums, and other facilities that require significant investment, but must remain state-owned. Among the shortcomings of this concession scheme, it should be noted that such projects are very complex in terms of technical and financial issues and require the involvement of professional experts and consultants in the field of restoration, archaeology, history, art history, etc. This, in turn, leads to an increase in investor costs and a conflict of interest between the benefits of the private and public sectors.

At the same time, a concession is much more profitable for the state as a tool for managing state property than, for example, a lease. The concession eliminates the possibility of so-called "hidden privatization", when the tenant of state property legally formalizes the ownership of inseparable improvements and actually requires the state to compensate for the cost of these improvements, or does not return the object under the control of the state. In the case of a concession, this option is excluded – here all investments belong to the state [37, p. 310].

It is impossible to ignore the fact that concession agreements are subject to all types of state guarantees for investments made by private investors. Thus, part 1 of Article 18 of the Law of Ukraine guarantees investors the stability of legislation and regulation of investment relations by the norms that were in force at the time of investment (except for tax, customs and currency legislation and legislation on licensing certain types of economic activity). The Law of Ukraine "On the Foreign Investment Regime", in turn, states that a foreign investor may require the application of the legislation in force at the time of investment for ten years".

Table 1. Advantages and disadvantages of concession of historical and architectural objects.

Advantages	Disadvantages
By attracting investments for the modernization or reconstruction of tourist facilities, the problems of their accident rate and destruction are solved, the national historical and cultural wealth is preserved.	Lack of a clear and sufficiently tested procedure for the use of state and municipal facilities and their assets (competitive selection procedure, distribution of concession payments, public control).
Creation of sources of revenues of concession payments to budgets of different levels.	Transferring the financial burden for reimbursement of the costs of restoration of the concession agreement object to visitors by raising prices.
For the concessionaire, the conditions for increasing the overall profitability of the business at the expense of significant economic freedom compared to the lease.	Legal support regarding the rights, obligations of the concessionaire, especially regarding tourist facilities, is not sufficiently regulated.
The formation of a competitive environment in the market of state and communal property, in fact, the absence of any competition explains the practical absence of progressive changes in the attractiveness of tourist facilities.	Direction of revenues from the use of the object of the concession agreement to finance projects not related to its operation, for example, the concession of the castle will provide for the construction of a hotel or restaurant in it.
The increase in tourist flows to objects, for example, castle tourism, will inevitably lead to the synchronous development of other enterprises of the tourism industry, as well as related industries (transport, catering, souvenirs, etc.), each of which is a source of tax revenues and new jobs.	There is a risk that raising prices will make it impossible for boarding school students, pensioners, and other socially vulnerable groups of the population who currently enjoy preferential tariffs to visit tourist facilities.
They make it possible to interrupt the concession agreement in case of violations by the concessionaire of its terms and conditions and return the object to state or municipal ownership.	Possibility of appropriation of the concession facility after the expiration of the concession agreement through illegal actions or amendments to the legislation.
They ensure partnership between the state and private business in solving priority tasks, in particular, during the concession of historical and architectural monuments, a number of tasks are solved, from stimulating tourist flows to preserving the national heritage of Ukraine.	They require significant tax and credit preferences in the conditions, since the object of concession agreements is characterized by low investment attractiveness and a high payback period of the project.
Ensuring significant cooperative and cumulative effects due to the economic growth of the tourist facility.	The risk of poor-quality restoration and reconstruction, which violates the historical and architectural value of the object.
Strengthening the competitiveness of castle tourism, strengthening its domestic and international positions.	The financial risks of the concessionaire grow into financial risks for the state property (the possibility of freezing construction and restoration works, as evidenced by two previous concessions of castles in Ukraine).

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The same regulatory act stipulates that foreign investments in Ukraine are not subject to nationalization, requisition and confiscation. However, the legislator provides for the forced termination of investment activities in case of violation of architectural norms, which should be clearly understood by the concessionaire who invests in historical and architectural objects, in particular palaces, castles, towers, estates, etc. This norm also significantly affects the level of investment attractiveness of tourist facilities, since it increases, in this case, the level of intervention in the activities of the investor by state bodies and carries the risk of termination of the concession agreement. In general, negative aspects of this kind should be compensated to the investor by other fiscal instruments to equalize the investment attractiveness at the intersectoral level.

3. Methodology

The concession payment based on the results of the concession tender or direct negotiations is calculated:

1) as a share (in percent) of the net income received by the concessionaire from concession activities according to the following formula:

$$CP = NI \times CPR \tag{1}$$

where CP is the amount of the concession payment, UAH; NI – net income for the relevant reporting period (month/quarter/six months/year) from concession activities (sale of products (goods, works, services) carried out in accordance with the terms of the concession agreement, UAH; CPR – concession payment rate, interest;

2) as a share (as a percentage) of the value of the granted concession facility, determined based on the results of its market valuation. For such a calculation, the estimated amount of the concession payment is determined according to the following formula:

$$CPe = (MV \times CPR) \div n \tag{2}$$

where CPe is the estimated amount of the concession payment, UAH; MV – market value of the granted concession object based on the results of its independent appraisal as of the date of appraisal of the concession object, carried out in the manner prescribed by the legislation on the appraisal of property, property rights and professional appraisal activities (excluding value added tax), UAH; CPR – concession payment rate, interest; n is the frequency of payment of the concession payment (determined in the concession agreement (month (12), quarter (4), six months (2), year (1).

The estimated amount of the concession payment is subject to mandatory indexation to the consumer price index.

In order to determine the concession payment in the concession agreement for the first reporting period, the amount of the concession payment for the base calculation period is determined by the following formula:

$$CPb = CPe \times CPI \tag{3}$$

where CPb is the amount of the concession payment for the base settlement period, UAH; CPe is the estimated amount of the concession payment, UAH; CPI is the consumer price index from the date of evaluation of the granted concession facility until the beginning of the first reporting period for which the concession payment is made.

The amount of the concession payment is determined by adjusting the amount of the concession payment for the previous period by the consumer price index for the relevant reporting period. If the concessionaire provides new concession facilities to the concessionaire during the term of the concession agreement, in accordance with the terms of such agreement, the concession payment may be increased in the manner prescribed by the concession agreement.

3) as a fixed payment, which may depend on the volume of goods, works or services provided by the concessionaire. A fixed payment is defined in monetary form as the product of payment for a unit of goods, work or service (hereinafter referred to as the payment) and the total number of units of goods, work or services. The amount of payment may decrease in the event of an increase in the volume of goods, works or services. The minimum thresholds for increasing the volume of goods, works or services that give grounds for reducing the amount of payment, as well as the maximum amount of such reduction, are determined in the tender documentation. The fixed payment determined in UAH is subject to indexation to the consumer price index in the manner and on the terms specified in the concession agreement.

The amount of the concession payment rate is determined based on the results of:

- concession tender and consists of the minimum concession payment rate specified in the tender documentation and the additional concession payment rate proposed by the winner of the concession tender;
- conducting direct negotiations, taking into account the conclusion on the expediency of making a decision on the implementation of a public-private partnership in the form of a concession.

Having considered all the above methods of concession payment, we can say that they all have certain shortcomings.

1) when finding the concession payment as a share (in percent) of the net income received by the concessionaire from concession activities, there are a number of risks:
   First of all, it is difficult to predict the amount of net income for, for example, a brewery in the Kushnirska tower of the city of Kamianets-Podilskyi, since the demand, commercial risks and features of the cost of the future business are not known in advance. Another disadvantage is that if the payment is paid upon receipt of net income, it may be shadowed by the concessionaire;
2) with the second method of concession payment as a share (in percent) of the value of the granted concession object, determined by the results of its market valuation, there are problems of market valuation of historical and architectural development. As an example, to estimate the market value of the Old Fortress of the city, if there are no analogues in the market, the object is unique, and the historical and architectural value has a very wide range of probable valuation. Here, the subjectivity of the appraiser is possible and there are potential risks of corruption agreements to underestimate the value of the concession object.
3) when calculating the concession payment as a fixed payment, which may depend on the volume of goods, works or services provided by the concessionaire, it is also difficult to avoid potential risks. For example, during a pandemic, when delivery is not carried out or during production downtime. After all, factors independent of the concessionaire interfere here. The possibility of preliminary agreements on the creation of favorable minimum thresholds for increasing the volume of goods, works or services is not excluded.

We, in turn, propose an alternative method of calculating concession payments, which will allow the most profitable public-private partnership for both parties to the concession agreement.

The proposed approach is based on the optimization problem of mathematical programming. The task of this optimization task is to determine the optimal concession payment rate, which will ensure, on the one hand, the target profit from the concession of the historical development object, and on the other hand, it will meet the interests of the concessionaire and serve as a guarantee that after the payment of concession payments, the entrepreneur will still have a profit, which is not always guaranteed by existing methods.

However, a very important point is that in this aspect we are talking primarily about the concession of historical and architectural objects. It is those castles, palaces, fortifications that are in disrepair that require significant budget investments (in their absence) and concession is the only way to preserve historical buildings.

The main requirement for this method is the preservation of profitability for the investor, while maximizing concession payments for the entity that concessions the facility, taking into account the costs of reconstruction and restoration ofthe facility.

Then the mathematical model of the problem will look like this:

$$Z = (NPV - Vr) \cdot x_i \to \max$$

$$\begin{cases} IRR\% \geq x_i < R\%; \\ x_i \geq i \times V_b; \\ (NPV - Vr) \times x_i \leq Wk. \end{cases}$$

where x_i is the concession payment rate; NPV is the net present value of the investment project; Vr – the cost of reconstruction, restoration, conservation (determined before the approval of the investment project); i – the interest is provided by law as the starting rent; V_b – book value of the object; R – discount rate in the market; Wk – is the market value of a long-term lease of a commercial facility similar in area; IRR – internal rate of return (reduces the risk of the investor to incur losses in the process of execution of the concession agreement); R is the cost of capital (discount) in the market or the rate of return on the investment project.

4. Results

Let's analyze investment projects in the tourism sector on the example of the city of Kamianets-Podilskyi [38]. All proposed investment projects fall under the direction of public-private partnership, which is an effective way to solve the problem of destruction of tourist facilities. In general, there are thousands of historical and architectural objects in Ukraine that need to attract investment resources. This is also confirmed by tourism projects submitted for funding from the State Fund for Regional Development. The vast majority of them relate specifically to repair and restoration works. Analyzing the objects of investment proposals in the field of tourism in Kamianets-Podilskyi, we see at first glance, quite attractive objects for public-private partnership. However, despite the very advantageous location in a picturesque canyon or in the historical part of the Old Town, we have a situation where for many years these investment projects remain offers and are not in demand. The main problems of the situation are:

- imperfect investment proposals, where there are no other data in addition to the above information
- the investor's need to work with historical and architectural objects and fulfill the requirement to preserve the authenticity of the object, to preserve its historical material and technical structure and form and the original architectural design together with valuable historical layers and allows to consider the object as a document of history and a work of architecture;
- the need for strict compliance by the investor with repair and restoration, construction, finishing standards;

Table 2. Justification of elements of the optimization model for determining concession payments.

Element of the optimization model	Argumentation of application
IRR Limitations	the internal rate of return reduces the investor's risk of incurring losses in the course of fulfilling the concession agreement.
Restrictions on the discount rate R (cost of capital in the market)	creates an automatic advantage of doing business over placing capital in order to obtain passive income.
Restrictions on the rate of return of the investment project	protects the investor's profit in the event of an economic crisis and does not allow the price of the concession agreement to exceed the profitability of the investment project.
Determination of the net present value of the investment project minus the cost of reconstruction, restoration, etc.	reduces, on the one hand, the costs of the concessionaire, at the same time allows the authorities to control the cost of performing these works and prevent violations of the historical and architectural ensemble of the city and destroy the uniqueness of the tourist site.
IRR Limitations	the internal rate of return reduces the investor's risk of incurring losses in the course of fulfilling the concession agreement.

- the high cost of not only renting tourist facilities, but also their restoration and design compared to the construction of a similar object built independently in the medieval style.
- lack of engineering communications (sewerage, water supply, gasification, electrification, Internetconnection), difficulties with establishing communications in historical monuments.

In fact, we have a situation where it is easier for a restaurateur to build a restaurant and give it an exterior design in the appropriate architectural style than to deal with numerous checks, architectural supervision, control by various state institutions. On the other hand, there are unacceptable problems similar to the situation with the Gonchar Tower (1583) and the adjacent synagogue (19th century), in which the Stara Fortetsia restaurant operates, where modern repairs have been carried out instead of authentic decoration.

It is obvious that despite the existence of legislative prerequisites for the conclusion of concession agreements in the tourism sector, the investment attractiveness of such facilities remains low.

We will calculate the cost of the concession agreement for one of the facilities that is in disrepair and requires significant budgetary investments. As an example, the object of the concession agreement is the Kushnir Tower. This object is presented among the investment proposals on the website of the Kamianets-Podilskyi city territorial community [39]. The monument is provided with a complex of buildings: “Furrier Tower”; “Wind Gate”; “North Gate”, the total area of the buildings is 433.8 sq.m., its detailed description and initial data to confirm the reliability of the calculations are given in the presentation materials [38]. The facility is in municipal ownership, which simplifies the procedure for transferring it to a concession.

An option for an investment project, taking into account the location, area and movement of tourist flows, can be a restaurant made in a medieval style with a suitable kitchen. Let's take as a basis the typical indicators of the development of the restaurant business in Ukraine, adjusted for the volume of the tourist flow of the National Historical and Architectural Reserve in Kamianets-Podilskyi in 2019. As a result, we will obtain the following indicators of the investment project.

Table 3. Output data for solving the problem of optimization of concession payments.

Output parameters	**Parameter value**
Object area, sq.m.	433.8
The cost of reconstruction and restoration (according to the approved amount of budget expenditures), UAH	3393632
Initial investment, UAH	8393632
Total discounted cash flow for 5 years), UAH	5,000,000
Profitability index (PI);	11822175.96
Net present value (NPV) (excluding reconstruction costs), UAH	(1746724.89 + 3051047.84 + 2664670.61 + 2327223.24 + 2032509.38)
Discount rate, %	2.36
Concession payment accrual base, UAH $\rightarrow$ max	6,822,175.96
IRR	14.5
Wk is the market value of a long-term lease of a commercial facility similar in area.	3428543.96

The mathematical model of the concession payment optimization problem will be as follows:

$$Z = (6,822,175.96 - 3393632) \times x_i \rightarrow \max$$

$$12,43\% \geq x_i \leq 14,5\%$$

$$x_i \geq 1\% \times Vb; (6,822,175.96 - 3393632) \times x_i \leq 1558800$$

where x_i is the concession payment rate.

The obtained results of the optimization model calculated by the simplex method are presented in table 4.

The proposed model will avoid a situation that has already been repeated twice in the city, when the Gate Tower collapsed under the weight of wet snow and due to an emergency condition, and due to improper restoration work, the New West Tower was destroyed, which, incidentally, proves the inefficiency of spending budget funds.

And taking into account the interests of the investor through the introduction into the optimization model of such indicators as the net present value of the investment project; the cost of reconstruction costs; the discount rate in the market; the market value of a long-term lease of a commercial object similar in area; the internal rate of return; the cost of capital, will not only reduce the investor's risk, but also guarantee the profitability of the project.

This, in turn, will avoid a repetition of the situation that occurred in 2013 in the Lviv region, when the experiment with the transfer of two castles (Tartakiv and Stare Selo) to the concession failed and none of the concessionaires began even emergency work. Kamianets-Podilskyi also has enough examples of violation of the authenticity of historical and architectural buildings, which can be observed in the results of repair and restoration work on Dovha Street and insulation of

Table 4. Budgetary and tax effect from the implementation of the optimization model for determining concession payments [40, 41].

Indicator	Value
x_i is the concession payment rate	0,476
The cost of the concession payment per 1 sq. m.	62.79
The cost of fulfilling the terms of the concession agreement for the concessionaire, per 1 sq. m, UAH	193.42
Annual cost of concession, UAH	326269.1
Budget effect	
The amount of revenues to the city budget from the delivery of the object to concession, UAH	1631345
Reduction of expenditures of the State Budget, UAH	3393632
Total budget effect, UAH	5024977
Tax effect	
Projected amount of tax liabilities:	
Value added tax, UAH	3 600 000
Profit tax	1,080,000
Single social contribution	2376000
Personal income tax	1944000
Social effect	
For residents: improving the historical and architectural ensemble of the city, reducing the risk of failure of the object, preserving historical and cultural monuments. For tourists: creation of tourist infrastructure facilities, increasing the tourist attractiveness of catering establishments.	

the facade of the ancient building of the Church of Peter and Paul with foam plastic. Another potential concession object may be the Tower on the ford (Art. 16), for the restoration of its roof, the Ministry of Culture and Information Policy of Ukraine allocated funds in the amount of UAH 1,232,000 in 2020 [42].

5. Conclusions

In the context of a shortage of budget funds for the maintenance and restoration of tourist infrastructure, in particular large-scale historical and architectural monuments, such as castles, fortresses, an alternative to a radical institutional shift is such a form of PPP as a concession that allows attracting private sector assets, but keeping economic objects in state ownership. For the tourism sector, which is characterized by both significant funding needs and a large number offacilities, this is most relevant. The concession regime eliminates the investment deficit and, based on positive foreign experience, will increase the fiscal return of attracting architectural monuments to active entrepreneurial activity.

The analysis of the search for alternative options for budgetary and tax incentives for investment attractiveness of historical and architectural objects is their transfer to concession. The most optimal form of the concession agreement for tourist facilities is determined by the ROT – "Rehabilitate – Operate – Transfer". However, the current methods of calculating concession payments allow possible neglect of the interests of the state or the investor. The application of the optimization model for determining concession payments to strengthen the budget and tax incentives for investment attractiveness of historical and architectural objects is proposed. Approbation of the optimization model at the historical and architectural site of Kamianets-Podilskyi showed budgetary and tax effects of UAH 5.025 million and UAH 8.028 million, respectively, and a social effect, which confirms the need for its use.

Along with this, further research and testing are needed to improve the legal regulation of the concession agreement and the mechanism for its implementation in the area under study, to guarantee the fulfillment of financial obligations by the investor and to expand the instruments of state participation in public-private partnerships in order to stimulate the investment attractiveness of the tourism industry.

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Ecological tourism in the industrial environment: A new vision

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Abstract. Ecologization of thinking and hedonization of life are processes that have greatly influenced motives behind ways to spend free time in recent decades. Ecotourism has become a way of exploring unique and exotic natural landscapes and a tool for their preservation Such an interpretation of ecotourism deprives residents of large industrial cities located far from such environmental sites of the opportunity to join the process of ecological cognition. The available sources analyzed by the authors interprete the concept of ecotourism merely through the environmental prism, the prism of the value of natural areas. The concept of ecological tours, which reveal only one aspect of ecology – the problem of protecting natural landscapes within specially protected natural areas/water bodies, is not yet developed either and is only interpreted as nature protection. The authors' interpretation of ecotourism and excursions as a type of industrial and sustainable tourism in the industrial environment is broader. Ways to settle environmental issues can only be found through understanding their essence. During eco-excursions, visitors can understand the nature and causes of the environmental crisis, emergence of global and local environmental problems and their consequences directly through observation, study, understanding, and experiment under the guidance of a qualified guide. Only real environmental emotional experience gained in the field can act as a driver for forming environmental behavior. The authors set out to interpret ecological tourism and ecological tours through familiarizing visitors with negative consequences of human impact on the environment; to reveal the content, methodological features of preparing and conducting ecological excursions; to perform a statistical analysis of ecological tours and excursions. Based on their own many years' experience in tour activities, the authors substantiate and characterize their own vision of ecological tourism and ecological excursions in the industrial environment, and establish the specifics of the excursion process related to ecological education and nurturing. The present research highlights problematic aspects of the classical concept of ecological tourism (its main limitation – by merely natural areas), the ecological excursions available in the world tour practice (merely nature-oriented or educational for schoolchildren/students), analyzes the methodological features of organizing and giving ecological excursions (identifies specific features of each stage of developing an ecological excursion, provides examples of methods from their own experience of excursion activities), and summarizes the authors' experience of ecological excursion activities at the theoretical and practical levels.

1. Introduction

The modern urbanized world, the world of technology and large information flows, the world of hard work, makes people look for various ways to fully recover their physical and mental strength, ways to learn and develop themselves during their leisure time. More and more people are considering the potential of eco-tourism when planning their free time. The concept of ecotourism emerged in the last century with recognition of the fragility of natural ecosystems, their rapid transformation due to human impact that could lead to extinction of both individual species of animals and plants and entire ecosystems. Several other factors have also contributed to the development of this type of tourism:

- realization of the value of natural landscapes in restoring human vitality as it is a well-known fact that from the time of Ancient Greece to the present, the ideal landscape for recreation is a natural landscape;
- saturation of the tourist market with mainstream cultural travels or "All inclusive" vacations;
- a desire to see, learn, and in some cases explore unknown natural corners of the planet;
- a desire to spend time actively, etc.

According to Cambridge Dictionary, ecotourism is the business of organizing holidays to places of natural beauty in a way that helps local people and does not damage the environment [1].

Ceballos-Lascurain, who formulated the leading principles of ecotourism, is considered the founder of this type of tourism William P. Stewart and Soehartini Sekartjakrarini [2,3]. However, as tourist demand for natural areas has changed, tourists' attitude to the value of natural ecosystems has changes as well, and negative alterations have occurred in the ecosystems themselves. In particular, Wang et al. note that conflicts of stakeholders' interests concerning development of ecotourism in environmentally fragile areas often negatively affect efficiency and effectiveness of ecotourism implementation [4].

Mondino and Beery also emphasize the fact that no matter how satisfactory the definition of ecotourism is, it does not qualitatively define the impact that this form of tourism can have on the cultural and ecological environment of the destination [5].

Thus, ecotourism is no longer inherently ecological or the one that ensures sustainable development of a tourist destination and especially a natural ecosystem. Therefore, there emerges a challenge of forming a new vision of ecotourism and possibilities of implementing its principles. This issue is particularly acute in industrial areas, such as Kryvyi Rih, where a large number of industrial enterprises engaged in iron ore mining, enrichment and processing are concentrated in a relatively small area. According to the authors, traveling to such industrial areas and landscapes radically altered by human activity and technology may be of ecological and educational value. These trips can then be called ecological excursions.

2. Publication overview

A thorough analysis of various sources of information reveals that different authors have diffenent understanding of ecological tourism and ecological excursions.

The relevance of the research is confirmed in [6] which shows that ecotourism has been developing rapidly in recent years, and the number of published articles is growing annually. The field of ecotourism research spans many disciplines and is a complex interdisciplinary subject. Ecotourism is also attracting the attention of many developed and developing countries. The United States, China, Australia, and South Africa are relative leaders in ecotourism research and development.

According to the UNWTO, ecotourism is defined as all nature-based forms of tourism in which the main motivation of the tourists is the observation and appreciation of nature as well as the traditional cultures prevailing in natural areas. It contains educational and interpretation features. It is generally, but not exclusively organised by specialised tour operators for small groups. Service provider partners at the destinations tend to be small, locally owned businesses. It supports the maintenance of natural areas which are used as ecotourism attractions [7].

Regarding the regulatory framework for the development of ecotourism in Ukraine, according to the current Law of Ukraine "On Tourism", Article 4 lists ecological tourism among a cohort of other types of tourism, and Article 6 lists ecological and rural tourism as priority tourism directions for Ukraine. At the same time, the Law does not define the concept of ecotourism [8]. The new Draft Law of Ukraine "On Tourism" provides a definition of ecotourism, but it is rather simplified. This type of tourism is interpreted as organization of recreation or obtaining natural or practical ecological knowledge and experience that does not harm the environment [9].

The authors of the article understand ecotourism as a type of industrial and sustainable tourism associated with visiting places the ecology of which is altered by man to this or that degree for the purpose of ecological education, awareness and nurturing. These are diverse landscapes that have undergone negative anthropogenic changes, recovered from such changes on their own, and have been reclaimed; or operating industrial facilities with a distinct ecological function (e.g. aeration plants that treat municipal waste water, waste sorting plants, solid waste landfills, etc.) [10, 11].

In the vast majority of sources, ecological excursions are considered a type of educational excursions into nature. Accordingly, their goal is to form an individual ecological worldview in order to prevent undesirable actions (aggression towards nature objects, cruelty) and provide targeted assistance to the child in the process of science education [12, 13]. The practice of Ukrainian and foreign educational institutions on organizing educational ecological excursions shows that they aim to highlight environmental problems and familiarize students with ways to solve them. Examples of these include excursions to waste management and recycling facilities (Ukrainian cities: Lviv, Khmelnytsky, Kyiv; German cities: Augsburg, Aachen, Zwentherdorf), a visit to the gasmeter in Oberhausen (Ruhr) for environmental education purposes, an environmental quest to collect garbage in Lviv parks, etc. Excursions to the waste water treatment plant Dresden-Kaditz are also conducted. However, the excursions that are offered in Europe to make people aware of global environmental issues are not visual observations of the sites of their manifistations. These excursions just introduce the problems and use modern technologies to demonstrate their consequences. The analysis of known practices shows that such excursions are not systematic, and the authors cannot find any scientific publications that would reveal the essence, features of organizing and conducting such ecological excursions and tours, or describe the ecological objects visited.

In the authors' opinion, the environmental responsible behavior is more likely to be shaped through direct observation and analysis of environmental objects and processes, e.g. observation of deforestation or landscapes transformed by accumulation of highly mineralized mine waters. Ecological excursions and tours should also be addressed not only to schoolchildren and students, but also to a wide range of visitors and ordinary people in order to broaden their general worldview, make them aware of modern technologies of solving local and global environmental problems, and build environmental culture and environmental behavior skills.

The analysis of various sources on organizing and conducting ecological excursions shows that they are understood as organized short trips to landscapes of special value in terms of nature, usually to specially protected territories and water areas of various conservation ranks [14]. In the English-language literature, the concept of excursion is usually interpreted as a short-term tour, and the term ecological excursion is extremely rare. The view of ecological tourism is traditional for this field and understood as "responsible travel to natural areas that conserve the environment, sustains the well-being of the local people, and involves interpretation and education" [14]. According to the authors of the article, this understanding of ecological excursions and ecological tourism omits an important fragment: there is no explanation, demonstration or clarification of the causes of biological diversity reduction (at all its levels), other environmental problems, the causes and consequences of the environmental crisis in general, i.e. only the result of environmental processes is shown without disclosing their causes. After all, the environment of modern man is created by not only natural conditionally undisturbed areas, but also by anthropogenic modifications of various shapes and depths industrial landscapes, mining areas, cultural landscapes, bad lands, etc.

As a result of their research, the authors found a concept of staycations which are ecological excursions similar to their own concept of ecotourism just like ecotourism, "staycation" is also a term representing an idea with a reduced ecological impact. Staycation, i.e., vacations spent at home or near home rather than traveling to distant places, have the potential to cause less environmental harm as less fuel (or no fuel at all if we consider electric vehicles) is spent. It also means more money spent at a local or national level and this consumption helps strengthen the economy, supports existing or new jobs and increases local resilience. A staycation is a form of alternative tourism that is fully in line with the slow tourism trend. Slow tourism invites you to live in the present moment. It encourages you to take your time, discover nearby landscapes, reconnect and spend more time outdoors in nature with the people you enjoy. Discovering or rediscovering the beauty of your city or region, which we often forget to notice due to stress and the power of habit is another potential benefit of staycation [15]. It should be noted that the concept of "ecological excursion" is intermediate between "ecotourism" and "staycation" as it is based on the principles of ecotourism and involves short trips aimed at exploring the nearby environment.

The authors of this work are practicing guides with many years of experience in the tourism business and are members of the All-Ukrainian Association of Guides and the National Tourist Organization of Ukraine. In 2015, for the first time, the authors developed and conducted the first ecological excursion for residents and guests of Kryvyi Rih to the local solid waste landfill. Later, several other routes discussed in more detail in this article, were introduced into practice.

Based on their own practice of organizing and conducting tours and excursions around Kryvyi Rih, communicating with tourists from different countries and regions of Ukraine, teaching ecological disciplines at Kryvyi Rih Pedagogical University, and conducting ecological learning practices, the authors have accumulated experience and understanding of ecological tours and their popularity with the general public.

3. Methodology

Objective. The article aims to interpret eco-tourism and excursions through the prism of familiarizing visitors with negative consequences of human impact on the environment; to reveal the content, methodological features of preparing and conducting ecological excursions; to perform a statistical analysis of the ecological tours and excursions conducted.

The research is based on systemic and dialectical approaches and the simultaneous use of theoretical and empirical methods.

The theoretical research is carried out using the methods of comparison, analysis, abstraction, concretization and generalization. The theoretical methods are used to study the concept of ecotourism and sustainable tourism, identify their similarities and specifics; analyze the concepts "ecological excursion", "excursion into nature", compare different approaches to understanding the essence, organization and guidance of excursions, specify the authors' interpretation of the concepts "ecotourism" and "ecological excursion". The theoretical methods are also applied when assessing the tourist potential of ecotourism objects, selecting elements of research to be performed by tourists during the excursion.

The empirical methods are aimed at both finding and confirming theoretical conclusions while identifying ecological processes and their negative consequences; collecting information about them; analyzing the geographical location, structure, dynamics, and accessibility of selected objects. Selecting and using various methods and forms of ecological education, preparing, organizing and conducting ecological excursions and tours are empirical processes as well.

The research methodology involves a combination of theoretical and empirical studies through a number of successive stages:

1. **Exploration of the territory.** In the course of field research and fulfillment of the tasks of ecological educational practices during 2000–2023, potential objects of ecological excursions and tours were identified.
2. **Development and testing of the authors' ecological excursions** lasted from 2010 to 2015, when theoretical foundations of the research were partially formulated and possibilities of using the selected forms and methods of excursion work with different target groups of visitors were tested out. Working versions of the authors' ecological excursions were actually developed.
3. **Implementation of the authors' ecological excursions and tours in the practice of tourism activities of the Public organization "Kryvbastur" (director – V. L. Kazakov).** Since 2015, the authors of the research have introduced ecological tours of Kryvyi Rih and ecological aspects into tours to Kryvyi Rih. At this stage, regular ecological excursions were launched and their elements were introduced in tour programs for the general public. This made it possible to confirm attractiveness of tourist objects for a wide range of visitors and non-ecology specialists, effectiveness of the forms and methods of excursion work used, to form an assessment of the tourist attractiveness of the developed ecological excursions and tours to Kryvyi Rih and, all in all, confirm correctness of the theoretical conclusions and formulate the authors' interpretation of ecotourism.
4. **The authors' interpretation of ecotourism.** For the first time, the research comprehensively substantiates the essence of ecological tourism and excursions as a type of industrial and sustainable tourism at the theoretical, empirical and methodological levels.

4. Results

Since the authors did not find any similar understanding of the definition of ecotourism and excursions in the analyzed sources, they made an attempt to generate such a definition using artificial intelligence (in order to confirm correctness of the direction of the theoretical research in a certain sense). When requested to define ecological sustainability tours, ChatGPT responded "They are organized trips or tours designed to educate and raise awareness about environmentally friendly practices, conservation initiatives, and sustainable lifestyle principles. These tours typically involve visits to sites, places or projects that exemplify and promote environmentally sustainable practices The main objectives include promoting understanding of the interdependence between human activities and the environment, showcasing innovative environmental technologies, and inspiring participants to adopt environmentally friendly behaviors. Such excursions can include a wide range of activities, from tours of renewable energy facilities and organic farms to visits to protected areas and seminars on eco-friendly living. The main goal is to encourage people to make environmentally conscious choices in their daily lives and to help preserve the natural world" [16]. Thus, the authors realize specificity of their own views of the issue and the importance of interpreting ecotourism and ecological excursions from the perspective of industrial and sustainable tourism.

The research has revealed the following important functions that ecological excursions perform :

1. They have a significant educational potential in shaping knowledge about the concept of sustainable development for the general public. The educational role of ecological tours is mentioned in many sources, e.g. [17] touching upon methods of forming environmental knowledge and knowledge of sustainable tourism development. The authors have established the importance of experimental and problem-based learning and case studies. These

methods are widely used by the authors of this article during outdoor classes (when teaching the educational components "Ecology and Ecotourism", "Industrial Tourism", and identifying the effect of Barry Commoner's laws of ecology through the local example of a solid waste landfill). Moreover, these teaching and learning methods prove to be useful, especially when dealing with environmental issues and gaining experience from local perspectives. It is also important to develop skills of systemic thinking, empirical learning, techniques and methods of raising ecological awareness, and scientific research skills during ecological excursions (for students and the general public).

2. They are an active form of leisure time, involving considerable physical activity, as ecological objects are usually within a walking rather than transport distance.
3. They create social value because they unite tourists with ecological ideas into a group of like-minded people and direct the community as a whole to possible solutions to environmental problems.
4. They have a significant economic effect (especially for single-profile cities like Kryvyi Rih) – they contribute to economic diversification through development of new sectors: tourism in general, and such types as industrial and ecological tourism.
5. In terms of sustainable tourism, they help to disperse tourist flows and do not create an excessive burden on popular tourist centers.

In addition, through demonstration of local environmental problems, concepts and even ecological skills are formed. Ecological tours promote ecological education and advocate for the sustainable development of the nature-society-economy system.

The analysis of information sources, personal observations of excursions, and self-analysis of excursion activities enable identifying certain problematic aspects in the traditional interpretation of the concepts "ecological tourism" and "ecological excursion":

1) there is no comprehensive definition of the concept "ecological excursion" that would correspond to the content of excursion activities for all segments of the population (not just schoolchildren and students) and objects to be visiteds (especially protected natural areas, parks, public gardens, etc.);
2) development and conducting of ecological excursions into nature are the responsibility of individual professionals (secondary school teachers and specialists of particularly protected areas), which significantly narrows the possibilities of interpreting environmental problems for all the public and does not form a comprehensive vision of the essence of nvironmental processes and phenomena;
3) there are no clear methodological recommendations on the specifics of preparing, organizing and conducting ecological excursions to "real" ecological objects, such as a solid waste landfill or a mine water sump;
4) the tourist market lacks ecological tours that would reveal the genesis and show the consequences of environmental problems (there are few examples of tours to waste processing plants and a few "pseudo-ecological" tours);
5) the niche in tourism and the concept of ecological excursions are not defined, as they are considered in the vast majority of sources as educational tours into nature, and in terms of content and essence are a type of ecological tourism.

The authors propose to understand ecological excursions as a focused demonstrable process of learning ecological objects, which takes place under the guidance of a qualified guide and aims to: form ecological knowledge, skills and abilities, observe ecosystems and processes, familiarize with environmental problems and negative consequences of human economic activity, form economical

use of natural conditions and resources in everyday life, expand the ecological worldview.

In the authors's opinion, this understanding of ecological excursions is quite broad and comprehensive, allowing formation of an ecological worldview not only by visiting concervation areas, but also by showing such territories/water areas that are in an unsatisfactory ecological condition, or show the consequences of unsustainable use of natural conditions and resources, and introduce "environmentally friendly" technologies and industrial enterprises.

The purpose of ecological excursions should consist in:

- revealing the essence of many global environmental problems and consequences of their manifestation on local examples;
- forming basic ecological knowledge (e.g., ecosystem, anthropogenic and cultural landscape, reclamation, solid waste landfill, B. Commoner's laws of ecology, etc;)
- developing the basics of research activities (when visitors are involved in an interactive ecological research analyzing the impact of a solid waste landfill on individual components and landscapes as a whole, drawing up an ecological assessment report on the state of surface waters, determining ways to treat wastewater, etc;)
- developing ecological skills (e.g., household waste sorting, better use of water, fuel, and other natural resources);
- broadening the worldview;
- forming an active way of spending recreational / leisure time.

Ecological excursions have a significant educational potential in shaping knowledge about the concept of sustainable development for the general public. They are an active form of leisure time, involving considerable physical activity, as ecological objects are usually within a walking rather than transport distance.

In view of the above issues, the authors of the article propose to analyze the essence, methodological and organizational features of conducting ecological excursions based on the their own practical experience.

Ecological excursions can be classified by content and objects (figure 1) into thematic ecological excursions to:

1) operating industrial enterprises that employ ecological and innovative practices:
   - solid waste landfills and waste sorting stations, waste processing plants;
   - enterprises producing environmentally friendly energy (solar, hydrothermal plants, etc.);
   - wastewater treatment plants;
   - heavy and chemical industry enterprises with modernized production (e.g. coke oven batteries No 5 and No 6 at ArcelorMittal Kryvyi Rih).
2) landscapes altered due to unsustainable use of natural conditions and resources:
   - mine water sumps;
   - facilities for production waste;
   - open pits and waste dumps;
   - mine failure zones;
   - altered riverbeds.

Elements of ecological tours can also be organically woven into sightseeing tours, especially in industrial cities (figure 2). In particular, the basic program of the sightseeing tour of Kryvyi Rih includes visits to the following objects that demonstrate landscapes formed by anthropogenic activity: coke production of the ArcelorMittal Kryvyi Rih metallurgical plant, iron ore open pits of the Southern Mining Plant, Red Lake – a mine water sump, failure zones of the Kozatska

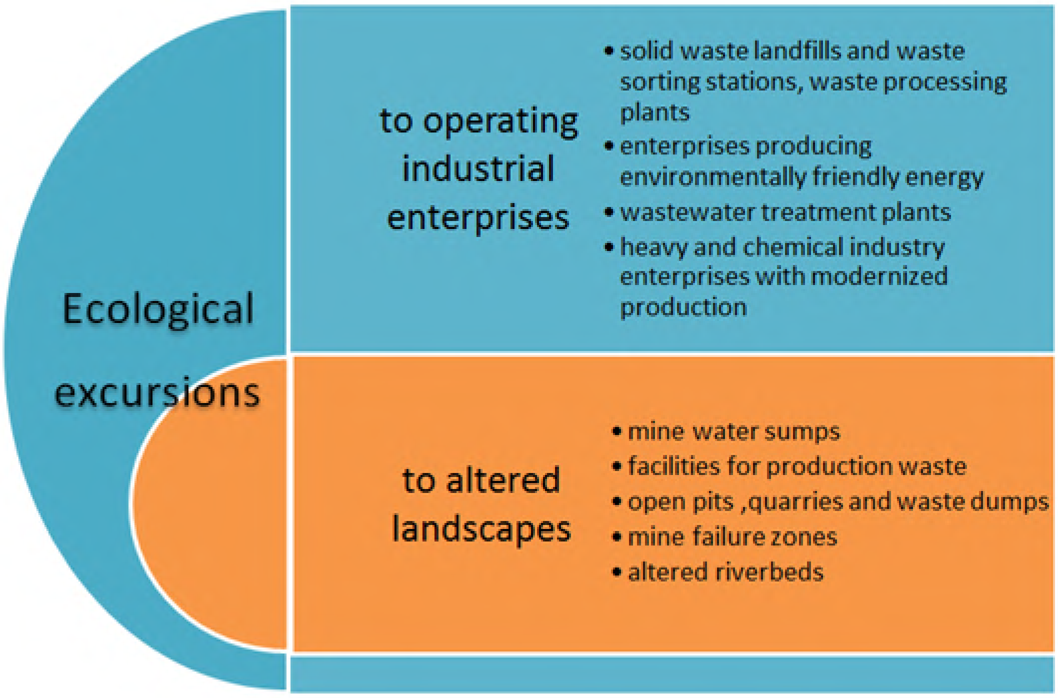

Figure 1. Types of thematic excursions by content and objects.

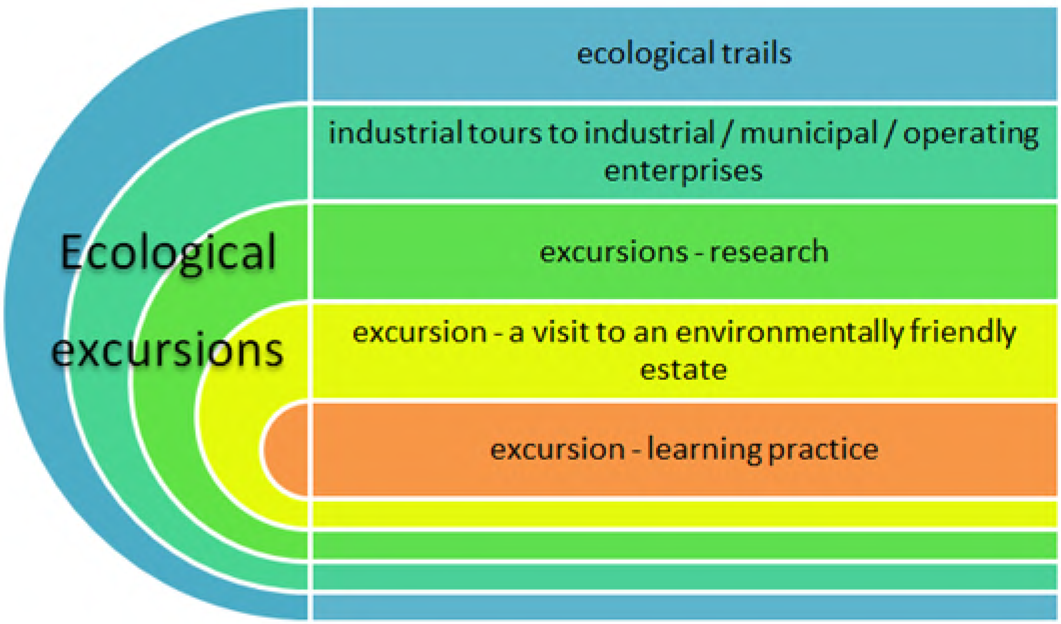

Figure 2. Organizational forms of ecological excursions.

mine, etc. When talking about Kryvyi Rih during a sightseeing tour, it is impossible to avoid environmental issues.

The experience of conducting ecological excursions allows distinguishing several organizational forms:

1) "ecological trails" – excursions in attractive and unique areas including demonstrations of ecological objects that are the result of the unsustainable use of natural conditions and resources (a mine water sump, altered ecosystems of the small Saksagan River, a dead pit, etc.), combining educational and recreational elements;
2) industrial excursions to industrial / municipal and other operating enterprises, where the raw material of production is usually the waste of another enterprise (examples in Kryvyi Rih include the waste sorting station, the waste processing plant, the procurement company "Clean City", the Central Aeration Station of the municipal enterprise "Kryvbasvodokanal", etc.), familiarize with specifics of technological processes, form knowledge of the environmental consequences of human activity for landscapes, create a positive image of enterprises, and build consumers' trust of these companies' services, make visitors aware of operation of environmental laws in real time;
3) excursions – researches, or scientific ecological excursions that aim to form elementary ecological knowledge and skills, when tourists have the opportunity to conduct a short scientific ecological investigation (excursions to the solid waste landfill involve preparation of an ecological passport and analysis of ecological links between various altered natural components, excursions along the Saksagan River involve surveying tourists regarding the attractiveness of the landscapes seen, etc.);
4) excursions – visits to an environmentally friendly estate, which familiarize a wide range of visitors with possibilities and efficiency of equipping a private house with solar panels, applying the principles of a closed cycle of resource use, waste sorting, etc.
5) excursions – learning practices conducted for schoolchildren and students and aimed at consolidating theoretical knowledge of ecological disciplines through practical experience, teaching ecological research methods and developing skills in their use, familiarizing with the city, etc.

The above organizational forms can be used altogether on the routes of ecological excursions, or fragmentally, combining several of them. For example, the ecological trail "Contrasts of the Saksahan River" combines the form of a trail and a research tour, as visitors are involved in collecting information about the attractiveness of Kryvyi Rih's industrial landscapes and fill out an assessment report on the state of surface water (using templates prepared by the guide).

The theme, purpose and objectives of an ecological excursion reflect its essence and purpose. The theme of the excursion is always underlain by basic ecological objects and phenomena. The theme defines the essence of the guide's story on the route. The name of the excursion should clearly reflect the theme and be formulated in such a way as to attract visitors. The name distinguishes the travel product from others on the market. For example, the authors called a series of thematic ecological tours of Kryvyi Rih "Breaking Conventions", in particular, an excursion to the mine water sump at the Hihant Hlyboka mine and the mine administration of the ArcelorMittal Kryvyi Rih metallurgical plant, thematically dedicated to the problem of utilizing highly mineralized mine water, was succinctly named "Breaking Conventions: Red Lake of Kryvbas", and vivid photos were selected accordingly when forming the market offer (figure 3). The purpose of ecological excursions is to develop elementary ecological competencies, broaden the worldview, and foster the economical use of natural conditions and resources.

Selection, study and assessment of ecological excursion objects. Ecological excursion objectss are often unique, sometimes exotic landscapes (even those located on the territory of industrial enterprises, such as aerotanks or wastewater lagoons), which, most importantly, demonstrate and explain the specificity of environmental problems and their solutions. Objects of ecological excursions are multifaceted, as there is no component of the landscape that is not affected by human activity: altered riverbeds, reservoirs, lakes in dead pits, mine water

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Figure 3. An advertisement for social networks (created by the authors in Canva).


Figure 4. Examples of ecological excursion objects (Red Lake, Solid Waste Landfill) (photos by the authors).

sumps, reclaimed areas of dumps, pits and tailings ponds; functioning solid waste landfills, anthropogenic and cultural landscapes (figure 4).

While developing any excursion, including an ecological one, the route developer must carefully assess available ecological objects according to several criteria: ecological character, safety of the visit, cognitive value and popularity of the object, its exoticism and uniqueness, expressiveness and preservation of the object, location and accessibility, and viewability. When developing an excursion, basic and additional objects must be identified; for ecological excursions, basic objects always include those demonstrating environmental issues, revealing the essence of the formation/solution of environmental problems. Additional objects can have both environmental and local history features.

The excursion route and its preliminary testing. Routes of ecological excursions are as diverse as the ecological objects. Depending on the travel mode, ecological excurcions can be walking and bus and walking tours. The route can be the same as on all other excursions: linear, circular or combined. The developer should arrange the selected excursion objects in accordance with the logistics of the visit, excluding: passing the same path more than 1–2 times, long journeys / transits between objects, etc.

Before implementing a new route for an ecological excursion, the guide must "walk/drive" along it in the field. the same is necessary in the case of a clear seasonality of the route: before the start of the new season, the route should be inspected for obstacles, emergence of new objects, changes in landscapes, development of the territory, etc.

The text of an ecological excursion should be scientific, based on reliable, verified facts, clearly and logically reveal the essence of the environmental objects shown to visitors, reveal environmental problems, and arouse visitors' reflection and suggestions for their solution. However, *delivery of the material and demonstration of objects during the ecological excursion should be easy, not burdened with complex terms and incomprehensible concepts.* The specificity of ecological excursions, especially to operating enterprises, implies the use of highly specialized technical terminology, so the guide of such routes must be professional in explaining complex terms in simple words when describing processes and phenomena (e.g. an aerotanks is a "jacuzzi for active sludge", "rock weathering" is the destruction of rocks, "solid waste landfill is a garbage dump"). The guide should always have additional information, as this provides good knowledge of the subject; texts of excursions are usually not fully reproduced during these excursions. At operating enterprises, the text of the ecological excursion is approved by their management.

"Guide's portfolio" and logistics of the ecological excursion. The "guide's portfolio" usually consists of the printed matter that complements the main content of the excursion and reflect the specifics of the objects shown (e.g., an enlarged photo of a blue bacillus on a tour of treatment facilities or a map of the route of the tour "Contrasts of the Saksaghan River" with the altered sections of the riverbed depicted, etc.). It is a good idea for the guide to have the opportunity to create a convenient electronic format of the "portfolio" using a tablet or laptop to allow additional use of video fragments or audio recordings, historical maps, chronologically arranged photos of a particular place, animation of the spread of pollution from its source during ecological excursions.

Ecological excursions are quite specific, so the guide shold have prepared templates for scientific research for certain routes (forms for filling out the environmental passport of the landfill, a sample of documents of the State Construction Standards for the construction of landfills, a form of the Surface Water Assessment Act, questionnaires for assessing the attractiveness of landscapes, etc.) If the excursion program provides for the study of physical and chemical properties of geocomponents, the necessary equipment should be available (e.g. a transparent glass flask for visual assessment of water clarity and impurity).

Certain routes may require additional equipment, e.g. a laptop (TV in the bus) to show a short video about the Kryvbasvodokanal enterprise and the specifics of the applied wastewater treatment methods for the tour "Revival of Kryvyi Rih Water" (to the Central Aeration Station). The guide should be ready to comment on the video and ask visitors questions about it.

Selection of techniques for showing and narrating on an ecological excursion. The showing and narrating methods are typical for all tours, but they reflect the level of the guide's professional skills. The distinguishing feature of ecological excursions is the use of generalization and abstraction techniques when telling about local environmental problems and the globalized character of their consequences. The narrative should employ specialized ecological and technological terms.

The technique of conducting an ecological excursion is characterized by the need to distinguish the ecological aspects of surrounding areas', landscapes' and objects' functioning. Since most of these excursions are walking tours, it is necessary to take into account field and weather conditions to choose proper clothing and footwear (figure 5). Ecological excursions to operating enterprises necessarily include an introductory safety briefing; in particular, when visiting the Central Aeration Station of Kryvbasvodokanal, heeled footware is prohibited. When giving ecological excursions, it is imperative to take into account all the requirements for walking tours (do not narrate until the whole group has gathered, choose areas for stops depending on the weather, provide for alternating active movement and rest along the route, etc.) The guide must have a first aid kit and be able to provide first aid.

The passport of an ecological excursion is drawn up according to a typical tabular scheme.

A trial ecological excursion is a mandatory stage in the development of an excursion route of any subject and it is aimed at walking around the route, making sure that the selected objects are correct and accessible for viewing, specifying paths, timing the excursion, selecting places for photography and rest. It is advisable to invite an experienced guide for a trial excursion. At the production facilities, the control excursion is tested by representatives and specialists of the enterprise itself.

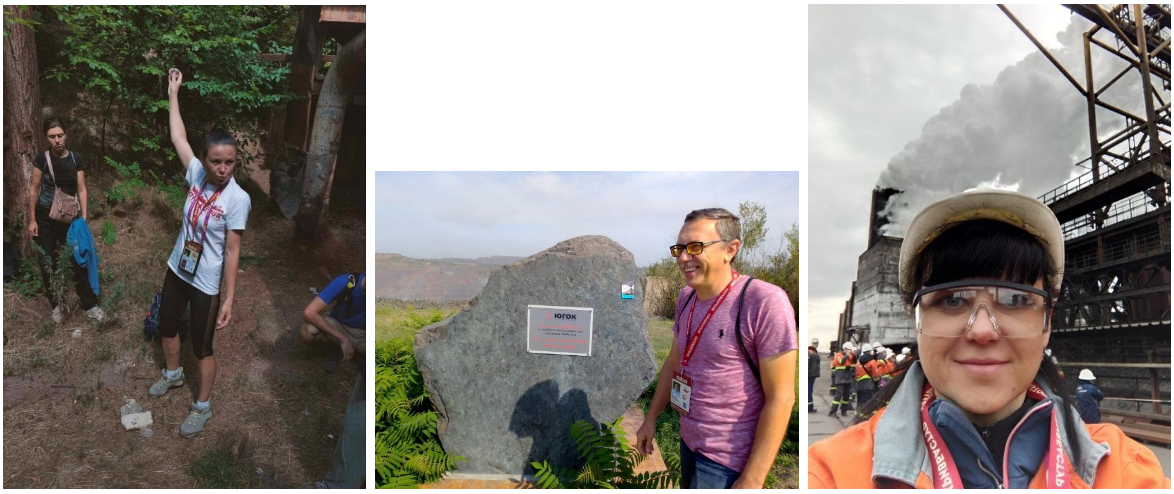

Figure 5. Fragments of ecological excursions guided by the authors of the article (photos by the authors).

There are certain requirements for professional skills of an ecological excursion guide: mastery of the conceptual and terminological apparatus of ecology and branch sciences (geography, biology, engineering, treatment technologies, mining, etc.), the ability to present information about operation of ecological objects, the system of relationships between landscape components and complex anthropogenic impacts in clear and simple terms are mandatory. The information presented should not be dry and the story should not be like in a textbook. The guide should present information in the form of a dialogue, discussion with visitors, use a variety of showing and narrative techniques, and control his/her voice. To dilute the scientific information, interesting facts and funny stories should be used (e.g. when visiting the Central Aeration Station in Kryvyi Rih, the guide asks visitors what the well-known abbreviation WC means. After hearing all the options, he/she says that it is a "water closet" – a toilet with a water flush of a modern form invented and patented in 1775 by the Scotsman O. Cumming). To enhance the "immersion" effect, interactive activities, including ecological games, quizes with valuable prizes (certificates for free participation in other excursions, samples of rocks and minerals from Kryvyi Rih basin, etc.) can be introduced.

The guide on ecological excursions does not have to have an ecological education, but he/she should possess relevant information on a high-level, experience in practical ecological research, a guide's qualification, and the ability to work with people regardless of their individual, age or other characteristics. Thus, to give ecological excursions at a high professional level, a specialist must undergo basic training in tourist skills and possess scientific ecological knowledge, skills, and abilities, have experience in practical ecological activities, and be able to present the excursion material in an easy, relaxed manner.

According to the authors, ecological excursions aim to create a proper image of landscapes and objects altered by human activity; reveal prospects for their functional content and further use; form an ecological worldview; transform consumer behavior. So, inherently, such excursions have a social value.

Take a closer look at the authors' ecological excursions.

The ecological excursion "Breaking Conventions – Kryvyi Rih Solid Waste Landfill" provides the opportunity to feel like an ecologist-researcher, as it involves the study and description of ecological processes that occur during the operation of solid waste landfills. The tour follows the route shown in Fig. 6, is a walking one and lasts up to 5 hours. It aims to introduce the problem of household waste disposal in Kryvyi Rih, environmental laws, develop waste sorting skills, teach visitors to identify environmental processes of the landfill's impact on the urban environment through simple observations and experiments, provide environmental education and develop skills in the economical use of natural conditions and resources.

During the excursion, the guide provides information on sanitary, hygienic, construction and environmental requirements and standards for the construction of a landfill, gives examples of more rational waste disposal, and tourists create an environmental passport for the landfill. Thus, a number of ecological concepts and ideas are being formed to foster a responsible attitude to waste sorting and recycling.

While observing the processes occuring at the landfill, the guide reveals the essence of the Laws of Ecology (by American ecologist B. Commoner): "Everything is connected to everything else", "Everything has to go somewhere", "Nature knows best", "There is no such thing as a free lunch" [18].

The excursion route passes along a road with heavy traffic of dump trucks loaded with oxidized ores that are dumped nearby into the pit. Due to this the road is bright red. In addition to ecological objects, the tour includes a look at industrial heritage objects (the pit of the Shmakivskyi mine, 1886; remains of a miners' village, early 1907; an old mine cemetery, 1900; a culvert under a railway line, 1893).

During the excursion, tourists can make an almost mountain climbing to the rocky waste dump consisting of various rocks and minerals, which brings elements of extreme, shows the possibilities of optimizing landscapes, allows the tourists to see the panorama of the southern part of the city and take many exciting photos. Also, the tourists can select individual mineral samples for their home collection as souvenirs.

As a result, the tourists get great impressions, master the skills of ecological culture, and some of them start sorting garbage after the excursion.

The ecological excursion "Breaking Conventions – Contrasts of the Saksahan River" is a walking tour along the Saksahan River, a second-order tributary of the Dnipro (figure 7). Its goal is to shape ecological knowledge of the process of forming the ecological state of water bodies (on the example of the Saksahan River) and the consequences of surface water pollution, to provide practical experience in identifying features of attractiveness of industrial landscapes, and to contribute to ecological nurturing. The program of the excursion includes

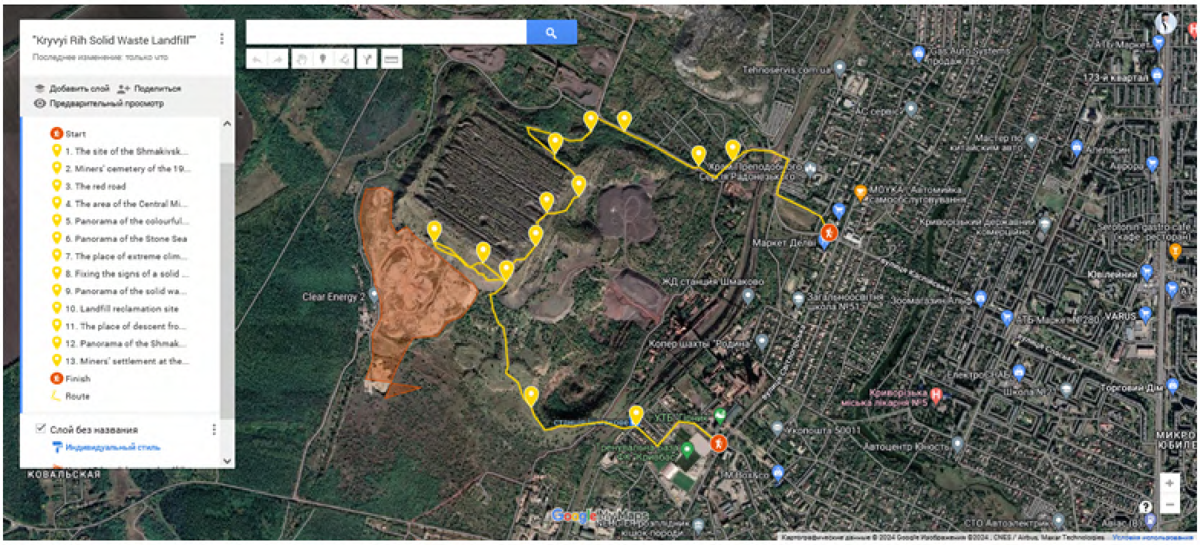

Figure 6. The route of the ecological excursion "Breaking Conventions – Kryvyi Rih Solid Waste Landfill" (compiled by I. Ostapchuk on Google).

a research: tourists under the guidance of the guide draw up an "Act of Environmental Assessment of the River", which characterizes the ecological state of the reservoir and the river valley, and familiarizes the tourists with the standards for changes in water quality and the state of the bank landscapes. After the Act is drawn up, the general ecological condition of the river and river valley is determined. The results of the research conducted during the excursion usually show their satisfactory condition. During the tour, the guide demonstrates natural and anthropogenically altered areas of the riverbed and river valley. The Saksagan riverbed underwent significant changes: – during 1929 – 1948, the KRES valley-type reservoir was constructed; – in 1960, the riverbed was straightened (the river meander Bazhanivskyi Kut was cut off); – in 1960, the river was diverted into an artificial rock canyon (the river meander Vechirnyi Kut was cut off), simultaneously discovering unique rocks of the Skeliuvata Formation of the Proterozoic, represented by quartz metasandstones, metagravelites, and metaconglomerates [19]. All these alterations are observed on just a 5 km long section of the river!

During the excursion, tourists are encouraged to pay attention to their own subjective feelings and impressions of the landscapes they see.

At the end of the trip, in one of the picturesque places, the guide offers to fill out an aesthetic valuation questionnaire. According to the results of visitors' assessments of the excursions, the landscapes of the lake in the KRES granite quarry and the landscapes of the Saksahan Canyon are identified as the most attractive.

Thus, the excursion of this kind is aimed at forming ecological, geographical and geological knowledge, showing positive and negative aspects of human impact on the global cycle of substances, revealing historical features of the area, including unique locations of Kryvyi Rih, and allowing tourists to capture their own impressions in vivid photographs.

The environmental excursion "Red Lake of Kryvbas" aims to show the features and some aspects of the environmental consequences of iron ore mining in Kryvyi Rih basin, to familiarize with the history of the Saksahan Reservoir, the Saksahan branch of Catherine's Railway, and the history of settling the area. The excursion is a walking one, lasts up to 4 hours, and is designed for a wide range of visitors. The main object of the excursion is a settling

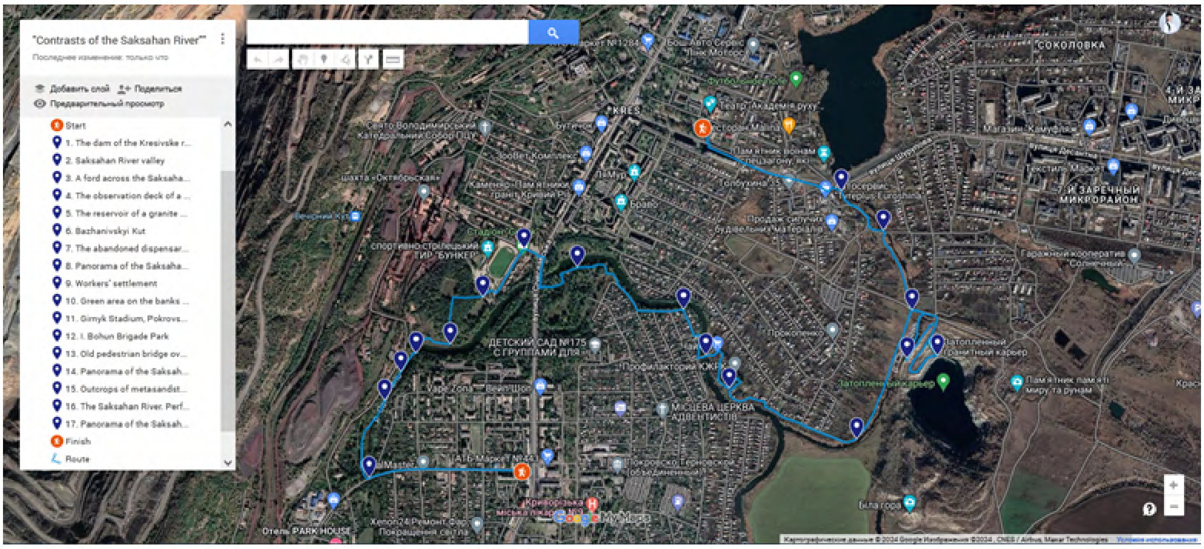

Figure 7. An excursion route "Breaking Conventions: Contrasts of the Saksahan River" (compiled by I. Ostapchuk on Google).

pond of highly mineralized mine water from the mines of ArcelorMittal Kryvyi Rih and Hihant-Gluboka, which is called Red Lake. There are many similar lakes in Kryvyi Rih, but this lake stands out among them: – it is easily accessible within the city; – it has "natural" shores; – it is partially reclaimed; – it has free of water areas with specific types of vegetation and wildlife; – scientists have substantiated that the chemical composition and genesis of waters are remnants of ancient seas (figure 8).

On the shores of Red Lake, the guide introduces visitors to the specifics of iron ore mining, the need to pump out groundwater (12–14 million m^3 annually, salinity of 35‰) and its primary treatment in such sumps. The narative is complemented by vivid examples and illustrations of how to avoid negative environmental consequences of such water treatment, possible alternatives are considered, and tourists' suggestions are listened to [10].

It is striking that the chemical composition of salts in these waters is alien to the water-bearing rocks; the chlorine-bromine coefficient testifies that the lake's salty waters are of marine origin. From Red Lake, a panorama of the nearest operating and mothballed mines opens up; tourists can see Kryvyi Rih TV tower, the Mudriona railway station, Kryvyi Rih Metrotram route, the unique Saksahan Reservoir, the history of which is connected with the construction of the Saksahan Derivation Tunnel (1957), etc.

Red Lake is located in a historical place where in the late 19th century there was landowner Halkovskyi's rich iron ore mine. Later, a dam was built, the Saksahans branch of Catherine's railway ran nearby and the Mudriona residential area was built (as a station settlement). There were always vegetable gardens and orchards in the Saksahan valley because of the 4-meter-thick layer of black soil, and daphnias were caught in the waters of the reservoir. The route then runs parallel to the high-speed tram line, enters the Mudriona railway station built in 1951, and ends near another building of the same station built in 1893, which is currently used as a warehouse.

This excursoin impresses foreign guests with its environmental friendliness and uniqueness.

The 4-hour bus and walking ecological excursion "Revival of Kryvyi Rih Water" (figure 9) aims to familiarize tourists with peculiarities of sewage treatment before it is discharged into surface water bodies in order to provide sanitary and hygienic safety in the region. The excursion provides environmental education and nurturing, and develops skills of the rational use

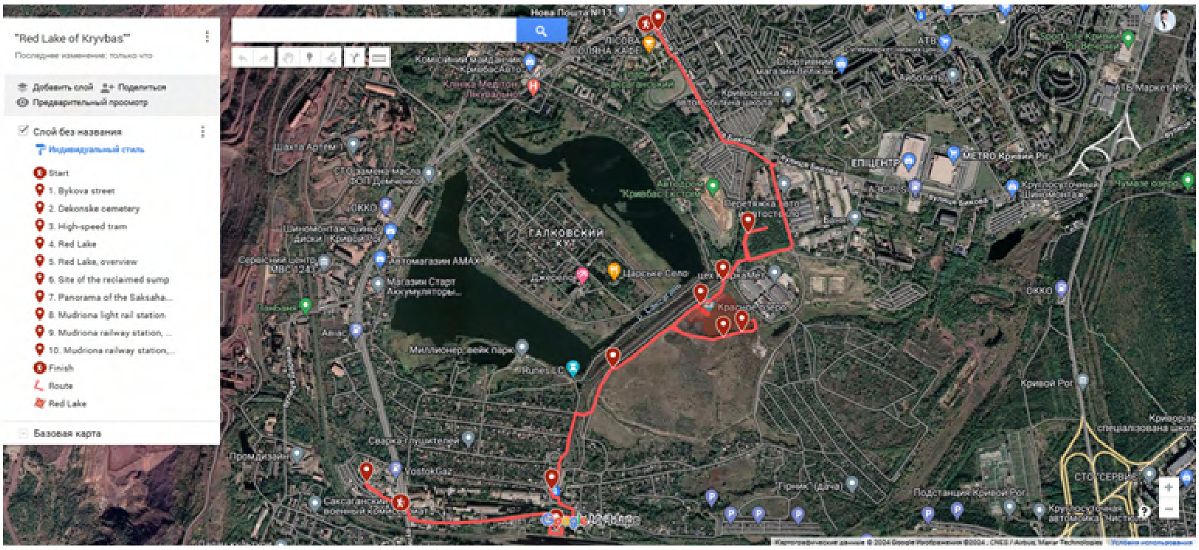

Figure 8. The route of the ecological excursion "Red Lake of Kryvbas" (compiled by I. Ostapchuk on Google).

Figure 9. The route of the ecological excursion "Revival of Kryvyi Rih Water" and the aerotank.

of fresh water. This is an excursion to an operating industrial enterprise – the Central Aeration Station (CAS) of the Kryvbasvodokanal utility enterprise, so a safety briefing is mandatory.

During the excursion, visitors get acquainted with the peculiarities of Kryvbasvodokanal's operation (since 1928), which helps to strengthen the company's image; learn the history of sewage treatment technology invention and creation of a water supply system in the city and the world.

The excursion of the Central Aeration Station is conducted by a guide and an employee of the company and covers the entire technological chain of water treatment: sewage – mechanical treatment at sand traps; biological treatment in aerotanks and methane digesters; water settling in primary and secondary settling tanks; chemical and/or physical decontamination; discharge into surface water bodies through a buffer pond.

The enterprise provides the opportunity to observe the operation of the units (air blower, cooling tower, primary and secondary settling tanks, aerotanks), walk across the bridge over the aerotanks, and talk to employees. During the narative, the guide draws attention to the systematic control of water quality, its compliance with the standards and current legislation of Ukraine.

The excursion ends with a visit to a buffer pond and a wastewater disperser, where the guide summarizes the information, verbally presents the technological chain and methods of water treatment, and reminds tourists of the need to use water economically in everyday life and during recreation near water bodies.

Ecological excursions – environmental learning practices. The authors have experience in giving similar excursions for students of Kryvyi Rih colleges (Mining Professional College and Inhulets College of Kryvyi Rih National University). This type of excursions is aimed at consolidating the previously studied theoretical material on ecology during the college course and developing practical competencies. Programs of such excursions are usually developed individually depending on the customers' requests. Most of them are bus and walking tours lasting up to 4 hours. The basic objects for the ecological practice excursions include Red Lake, the waste dump of the Central Mining and Processing Plant, the solid waste landfill, and other options:

Hannivka iron ore pit of the Northern Mining and Processing Plant, the mining equipment skansen of the same enterprise, Pershotravnevyi mine and the Obiednanna underground mine, the KRES granite quarry, and failure zones in the Kozatska underground mine area.

In contrast to ecological excursions that are conducted for the general public and taking into account the specifics of the order, the program of this excursion contains more information on theoretical ecology (the effect of environmental laws, environmental factors, ecosystems, etc.), iron ore mining and processing technologies, environmental problems of the city and methods of their solving.

Much more attention is paid to development of research skills and practical ecological competencies, e.g. investigation of the ore dust spread depending on the topography and distance from the source of pollution; identification and description of existing and possible ways to reclaim post-industrial landscapes; preparation of an environmental and sanitary passport for a solid waste landfill, drafting an ecological assessment report for surface water or developing ways to utilize highly mineralized mine waters, etc.

Ecological excursions-practices necessarily contain elements of local history, as when moving between sites, the guide tells not only about environmental issues, but also provides interesting facts from the historical past of different parts of the city and mines, reveals the specifics of forming an industrial city from ancient times to the present, guides students by the names of certain objects, and reveals the role of famous figures in the development of the city, shapes certain geographical knowledge.

Participants of excursions-practices are better prepared to perceive scientific information (due to their studies in specialized institutions) and learn certain practical skills. This type of excursion is in demand among the educational institutions of the city.

The authors began offering ecological excursions on the tourist market of Kryvyi Rih in 2016. The intensification of this excursion activity was due to the implementation of measures adopted in the municipal programme for the development of industrial tourism [20, 21]. Figure 10 shows the dynamics of thematic ecological excursions in the city. The exceptions were 2021 due to the authors' participation in other projects, and 2022, when no tours were conducted at all due to military operations. As a result, one can see the largest total number of ecological excursions (21) in 2017. The lowest number was recorded in 2020 (5) due to the COVID-19 pandemic, and in 2023 (6) due to the city's frontline position. Currently, holding mass events is also aggravated. At the same time, there was no significant dominance of excursions on specific themes during the period under review. Excursions to the Central Aeration Station "Revival of Kryvyi Rih Water" attracted quite a steady interest of visitors, but they have not been held since the beginning of the quarantine and subsequent military operations. There are fewer excursions in the format of learning practices due to the narrow target audience.

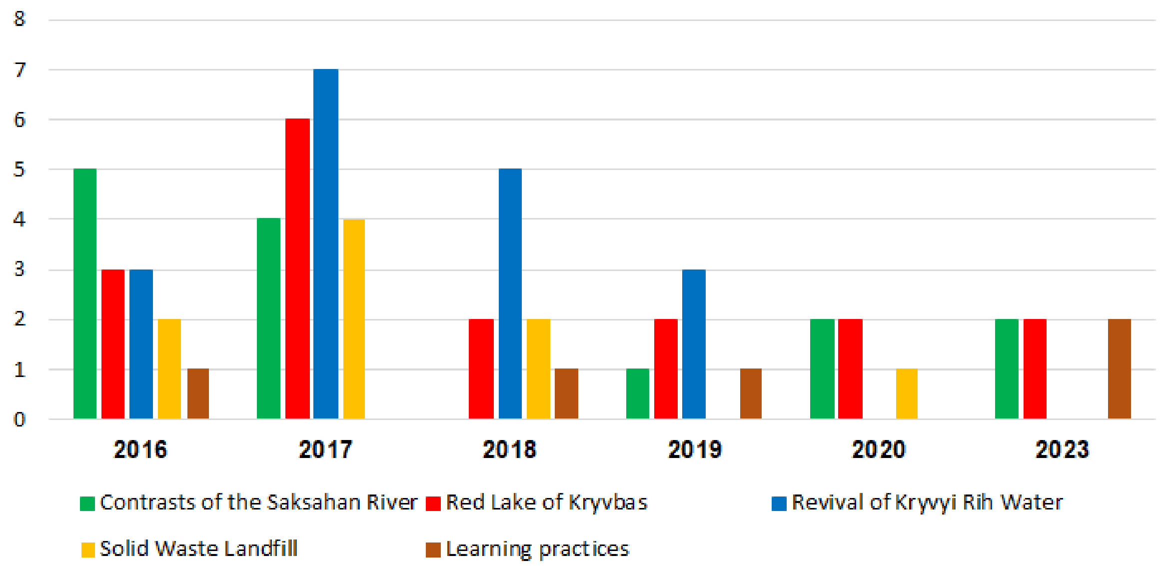

Figure 10. Dynamics of ecological excursions in Kryvyi Rih in 2016–2023.

In total, the authors organized 63 ecological excursions during this period. This relatively small number is due to the fact that the authors are scientists and organize tours not for commercial purposes, but to popularize their ideas and test certain hypotheses. The generalized data for the entire period of these excursions (figure 11) shows that "Revival of Kryvyi Rih Water" was the most popular one which dominated in terms of the total number of excursions conducted (18), the number of visitors (362), and the average group size (20.1 persons). "Red Lake of Kryvbas" and "Contrasts of the Saksahan River" were somewhat less popular. A smaller number of excursions were organized to the solid waste landfill due to the specifics of this subject. However, the average group size (19.8 persons) was also quite large. The lowest number of excursions (5) and visitors (72) was recorded among the learning practices with an average group size of 14.4 persons. This was because of the distance learning of students and the fact that some young people have left the country due to the war, and others can only be involved in excursions if they comply with all safety requirements, which is quite difficult in today's reality.

In addition to purely ecological excursions, the authors of the article are involved in development and implementation of other city excursions and tours of various duration to Kryvyi Rih. The environmental and social aspects of these tours cannot be avoided.

Thus, the main, basic objects during a one-day tour to Kryvyi Rih ("Technogenic Fiction in Kryvyi Rih" from the tour operator Krayina UA) include the following: iron ore pit of the Southern Mining and Processing Plant, coke production of the ArcelorMittal Kryvyi Rih metallurgical plant, the monument to Kozak Kryvyi Rih, the Flower Clock, Kryvyi Rih Metro – a high-speed tram, Red Lake, the KRES granite quarry, Kozatska mine sinkholes, Kochubeyivski

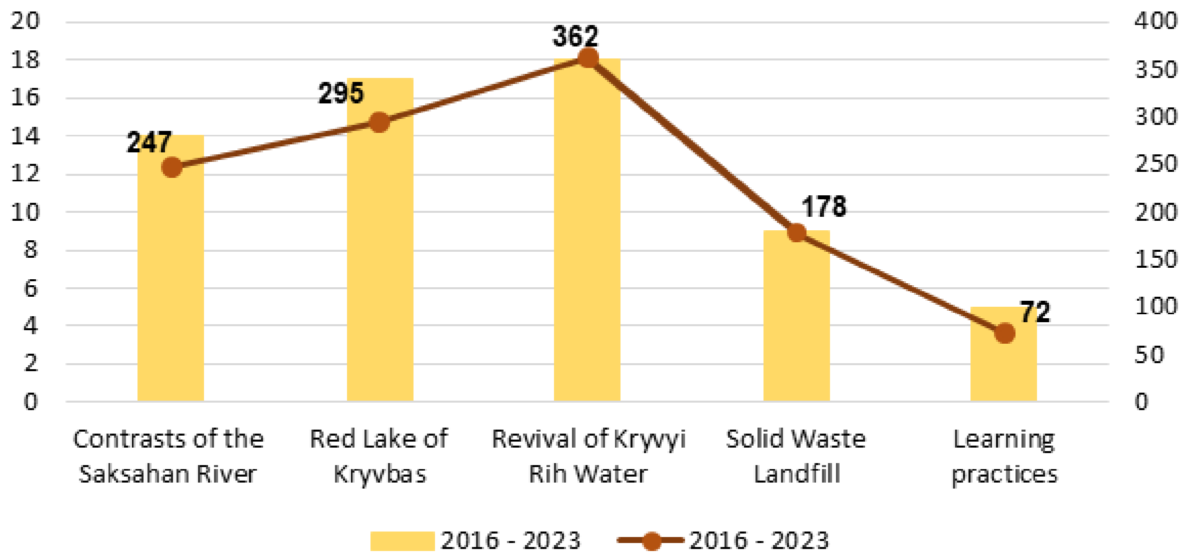

Figure 11. Analysis of ecological excursions in Kryvyi Rih and tourists coverage in 2016–2023.

adits. When visiting industrial enterprises, environmental issues inevitably arise, ranging from the "environmental friendliness" of blasting operations in the pit, safety of coke production gases emisstions, environmental problems of utilizing and recycling pumped-out highly mineralized mine waters, to safety of working conditions for employees and approaches to landscaping the city.

Table 1 presents details of the environmental aspects of visiting some tourist objects in Kryvyi Rih.

Table 1: An example of the environmental content of tourist objects in Kryvyi Rih

No.	Name	Main technological process	Environmental phenomena and processes, problems that are objects of observation
1	Iron ore pit at the Southern Mining and Processing Plant (430 m deep, 3 km in diameter).	Extraction of magnetite quartzite, drilling and blasting operations, transportation of extracted raw materials (iron ore and waste rock), groundwater pumping.	Earth's crust disturbances, groundwater disturbance, landslide processes on pit walls, air pollution with dust and gases, man-made earthquakes, destruction of soil and biota, formation of new landforms, formation of anthropogenic landscapes, production waste disposal and recycling.
2	Coke production at ArcelorMittal Kryvyi Rih	Production of coke for blast furnaces of the metallurgical plant.	Air pollution with harmful substances: solid aerosols, water vapor, carbon dioxide, hydrogen sulfide, nitrogen oxides, ammonia, benzopyrene, etc. Thermal air pollution, participation of the production in formation of an urban heat island and global climate warming. Formation of a typical industrial factory landscape instead of that of natural steppe.

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Table 1 – continued from previous page

No.	Name	Main technological process	Environmental phenomena and processes, problems that are objects of observation
3	Red Lake	Logistical intermediate storage of highly mineralized groundwater pumped out of the underground mine, hematite sludge settling and pumping of water to the main mine water storage pond in Svystunov gully.	Movement of deep groundwaters (from a depth of 1–1.3 km) to the surface. Mine waters with high mineralization is not utilized, but transported further to a large pond for discharge into the Inhulets River. Pollution of surface waters by highly mineralized mine waters. Air pollution with red hematite dust in summer due to dust storms. Formation of atypical halophytic vegetation communities. Ways of solving the problem of mine water treatment and utilization (current and prospective).
4	KRES granite quarry	Granite extraction, waste rock storage in a nearby dump, granite crushing.	Air pollution by dust and gas emissions, destruction of natural topography, soil, vegetation, landscapes, etc. Formation of the ‘second” nature – industrial landscapes of the pit and waste dump, emergence of a lake in the dead pit, emergence of derivative natural phenomena – landslides, crumbling and collapse of granite mass. The problem of anthropogenic impact on the processes of rock destruction and the impact on the global biogeochemical cycle of substances.
5	Sinkholes of Kozatska mine	Mining of minerals – rich iron ore and extraction of associated rocks – shale and quartzite. Reclamation of sinkholes by backfilling with crushed waste rock.	Deep and planar deformations of the geological structure, formation of gigantic depressions above the mined-out space (voids), landslides, collapses, washouts, destruction of residential settlements, fatalities and destruction of the city’s mine infrastructure resulted from natural manifestation of sinkholes. Possible ways of reclamation of the areas disturbed by sinkholes.
6	Kochubeyivski adits	Iron ore mining in the early XX century.	Deformations of geological structure, formation of underground cavities (adits, vertical passages, underground mining rooms), emergence of industrial landscapes of the pit and dump.

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Table 1 – continued from previous page

No.	Name	Main technological process	Environmental phenomena and processes, problems that are objects of observation
7	Sludge storage facilities – Obiednane, Voikivske, Hrushovatske – of Inhulets, Central and Northern mining and processing plants.	Storage of sludge, a waste product from processing poor iron ores, using pipes (slurry pipelines).	Air pollution by dust, destruction of soil and vegetation, flooding of land by infiltration and condensation water, formation of new landforms, drainage of infiltration water, reclamation, the risk of man-made mudflows, accidents on slurry pipelines and pollution.

5. Conclusions

Ecotourism in its classical interpretation involves the study of natural landscapes in their natural state (mainly within specially protected areas), but not all regions of the world have high natural resource potential. For example, industrial regions, such as the city of Kryvyi Rih, which have been heavily transformed by human activity and technology, are characterized by a new industrial artificially created environment. However, this does not mean that there are no eco-tourism facilities in such ares. In the authors' opinion, the situation is quite the opposite – observations, study, and analysis of industrial landscapes, environmental situations of varying degrees of severity, formation of environmental problems and methods of solving them, etc. are perhaps the best option for ecotourism objects.

Ecotourism, in the authors' interpretation, is a type of industrial and sustainable tourism. It is aimed at traveling to ecological tourist objects (not necessarily natural) that demonstrate manifestations of various environmental problems and their consequences in order to carry out ecological education and nurturing. These include various landscapes that have undergone negative anthropogenic changes, have recovered from such changes on their own or have been reclaimed, and operating industrial facilities with a clear ecological function (for example, an aeration plant where municipal wastewater is treated, waste sorting plants, solid waste landfills, etc.)

Ecological objects in the industrial environment are the ones of both eco-tourism and ecological excursions.

Ecological excursions aim to create a proper image of industrial landscapes and objects altered by human activity; reveal the prospects for their functional content and further use; shape an ecological worldview and personal responsibility for global environmental issues; transform consumer behavior into a responsible attitude towards the use of natural conditions and resources; implement sustainable development goals in everyday life.

The authors of the research are practicing guides who have developed and conducted ecological tours and excursions in Kryvyi Rih. The specificity of the developed ecological excursions consists in the fact that they are available to a wide range of visitors: both schoolchidren and students, as well as city residents, domestic and international tourists, and are aimed at visualizing global and local environmental problems and learning about the industrial environment through interactive participation in a simple scientific ecological investigation, identifying local environmental problems and clarifying their personal role and responsibility in emergence of global problems of humankind.

The authors have created four routes of thematic ecological excursions, which aim to form an understanding of global problems of humanity through local examples of unsustainable use of natural conditions and resources, through personal experience of observing, analyzing and assessing various ecological situations in the industrial environment. These excursions with an enhanced research component are used to conduct ecological training practices for students of Ukrainian educational institutions.

During testing, some ecological objects proved to be so attractive that the authors included them in the programs of tours around Kryvyi Rih. In general, a visit to our city cannot do without touching upon environmental issues even during a sightseeing tour. The basic objects in the program of a one-day tour to Kryvyi Rih (e.g. "Technogenic Fiction in Kryvyi Rih" from the tour operator Krayina UA) include the following: iron ore pit of the Southern Mining and Processing Plant, coke production of the ArcelorMittal Kryvyi Rih metallurgical plant, the monument to Kozak Kryvyi Rih, the Flower Clock, Kryvyi Rih Metro – a high-speed tram, Red Lake, the KRES granite quarry, the Kozatska mine sinkholes, Kochubeyivski adits. During the tours, visitors most often ask environmental questions ranging from the "environmental friendliness" of blasting operations in the pit, safety of coke production gases emisstions, environmental problems of utilizing and recycling pumped-out highly mineralized mine waters, to safety of working conditions for employees and approaches to landscaping the city.

During 2016–2023. (excluding 2021, 2022 – pandemic and martial law), the authors of the research conducted about 80 ecological excursions (excluding sightseeing tours) for 1500 tourists. "Revival of Kryvyi Rih Water" was the most popular excursion before martial law, but now its objects are strategic facilities of the city's infrastructure). "Breaking Conventins – Kryvyi Rih Solid Waste Landfill" was the least popular route.

In general, the ecological excursions developed and introduced in excursion activities by the authors of the research are relevant for the whole world, and while in some countries such excursions are conducted for schoolchildren and students, in Kryvyi Rih ecological excursions have been tested and are available for a wide range of visitors.

Thus, ecotourism in the industrial environment is a new interpretation of the traditional concept. The authors' interpretation of ecotourism and excursions, in contrast to the existing concepts and approaches implemented in the world practice of excursion and tour operator activities, expands the possibilities of forming ecological competencies, implementing ecological education, broadening the worldview, forming an active way of spending leisure time, economical use of natural conditions and resources in everyday life for all segments of the population regardless of age, social affiliation, etc. As a result of direct observation of real ecological objects and functioning industrial enterprises, and personal investigations of environmental processes, visitors gain their own experience of learning about environmental problems in the industrial environment, which effectively directs further human behavior and life towards the mode of "sustainability" and "environmental friendliness". If the guide uses carefully selected environmental objects and interactive methods and techniques of ecological education and nurturing, the visitor gets a positive experience and emotional trace after the excursion, and an actually formed skill of environmental behavior. These and other aspects of ecotourism in the authors' interpretation are of particular importance for achieving the goals of sustainable development.

A new look at ecotourism in the industrial environment can be a way of rethinking the essence of classical concepts. The involvement of industrial and post-industrial landscapes (not only as industrial tourism objects), functioning industrial enterprises, reclaimed and revitalized spaces in the ecotourism sector will significantly expand the possibilities of achieving the goals of ecological education and nurturing and shaping the ecological worldview of all residents of the planet Earth. Within Kryvyi Rih, it would be advisable to create an ecological park on the territory of non-functioning production areas or facilities, which would present expositions on the ecosystems of the region/Ukraine, anthropogenic landscapes depending on the direction of use, and the possibilities of waste-free technologies. This park could be filled with interactive elements that would allow visitors to simulate the effects of technogenesis. This interpretation of eco-tourism allows understanding the nature, causes of global environmental problems and possible methods of solving them through understanding the participation and responsibility of everyone. For example, unsorted garbage accumulated in a solid waste landfill today will result in pollution and deterioration of drinking water quality, or inavailability of a favorable recreational environment, or contamination of soil and food grown on it, or all of these consequences together. Real-time visual observation of the entire cause and effect chain is perhaps the best way to shape environmentally sound human behavior. Just watching a movie about global environmental issues can have an ecological and educational impact, but it is quite clear that once visiting a sewage treatment plant, the visitor will definitely understand the rules for using sanitary appliances in everyday life, join in saving water, not clogging sewage systems with garbage, etc. Similarly, it is more effective to develop waste sorting skills through visits to waste processing plants when the consumer understands possibilities of saving natural resources through implementation of recycling and reuse technologies.

These examples confirm the timeliness of the authors' theoretical research and its practical results; the environmental, economic, and social significance of ecological excursions and tours implemented in excursion activities; opportunities for further theoretical and empirical research on ecotourism in the industrial environment.

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Sustainable development strategies in the field of tourism and recreation in war conditions in Ukraine

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Sustainable development strategies in the field of tourism and recreation in war conditions in Ukraine

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Abstract. For Ukraine, the question is very acute today: will Ukrainian business be able to continue its activities in war conditions and support the state's economy. In the conditions of war, it is extremely difficult to solve many practical issues related to the problems of forming a business strategy based on the principles of sustainable development. The basis of which are ecological interests of society, eco-oriented development of companies, constant consumption and production. The article examines the peculiarities of the operation of tourist companies in the conditions of war, conducts a basic STEEPLE analysis, presents five illustrative cases of the experience of the operation of tourist companies during the war, defines the main components of strategies based on the principles of sustainable development and new formats of Ukrainian tourism in the realities of war. The purpose of the research is to study the practical experience of conducting activities in the field of tourism during the war in Ukraine and to develop recommendations for the formation of a strategy for the ecologically oriented development of tourist companies during the war.

1. Introduction

1.1. Research question

For Ukraine today, the question is very acute: will Ukrainian business be able to continue its activities in war conditions and support the state's economy. It is impossible to win a war without the proper functioning of a business. This means that businesses must operate, provide jobs, pay taxes, and provide the country with an important resource to defeat the enemy. To do this, it is necessary to create appropriate conditions and an appropriate institutional environment, using all available capabilities and reserves. In war conditions, it is extremely difficult to solve many practical issues related to the formation and implementation of an appropriate business strategy. This is especially relevant for industries whose functioning depends on the level of safety and stable rates of economic development, in particular for enterprises in the tourism and recreation sector. Enterprises of these industries, due to the specifics of their activities, have an anthropogenic impact on the environment and are capable of causing destructive environmental phenomena. Further development and restoration of tourism and recreational facilities will require the use of new views and approaches to the development of business strategies, as well as proactive entrepreneurial decisions on the part of market participants, since

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the state, given the continuation of the war, will have other financial priorities. Such strategies must necessarily be environmentally oriented. In modern conditions, debate continues among scientists on theoretical and methodological approaches to the formation of environmentally-oriented development strategies [1].

The research question in this article consists in the analysis of methods of improving strategies in the field of tourism and recreation in Ukraine, based on the adaptation of strategic management methods and attention to sustainable development. The use of proactive strategies for the sustainable development of enterprises in the field of tourism and recreation will allow market participants to make strategic decisions necessary to increase competitiveness, including in the ecological vector.

1.2. Related work

The issue of forming an activity strategy is important for the successful functioning of a business [2]. Whittington et al. define strategy as the long-term direction of an organization [3]. Porter [4] noted that strategy determines a company's specific approach to competition and the competitive advantage on which it will be based. Mintzberg [5] emphasizes that strategy is a certain pattern in the flow of decisions. However, in war conditions, the company must take into account the rapidly changing situation in the external environment and count on its own potential. Therefore, in our research, we proceed from the fact that strategy is the determination of promising guidelines for the company's activities based on an assessment of its potential capabilities and forecasting the development of the external environment.

Companies operating in turbulent market conditions usually implement several main stages in the formation and implementation of a strategy. This is primarily the development of a strategic vision, setting goals, developing a strategy for achieving goals, implementing a strategy, monitoring development, evaluating results and making adjustments depending on the situation in the environment. However, in war conditions the situation with making strategic decisions is different. Firstly, the time frame for strategic planning is short, since war can destroy all plans quite quickly. Secondly, because of the war, entrepreneurs must decide for themselves to function at the moment or not, or to change the direction of activity, or to offer a new product depending on the situation that develops from the outside. Thirdly, when developing a strategy, it is important to take into account the social component of the strategy. The last component plays an important role during the war. We believe that every business during this period should be socially oriented. This concerns the provision of jobs, environmental protection, corporate volunteering, etc.

1.3. Problem statement

The scientific problem is the use of strategic management and planning tools to increase the effectiveness of enterprises operating in the field of tourism and recreation in the conditions of war on the territory of Ukraine. In the public discourse of Ukraine in pre-war times, more attention was traditionally paid to the development of state and regional programs to support the sphere of tourism. However, during a war, the state has other priorities related to security, economic and social issues. Therefore, the study of the state of the external environment, the structuring of the factors of action, the study of the best practices of the development of companies in the field of tourism and recreation during the war represents significant enthusiasm.

The hypothesis of the article has both a theoretical and an applied basis and concerns the need to strengthen the level of strategic management at the micro level, taking into account the destructive influence of military actions and changing the priorities of state policy.

The purpose of the article is to study the practical experience of making strategic decisions for enterprises in the field of tourism and recreation in the context of sustainable development in the conditions of war in Ukraine. Based on surveys of business representatives, consumers, industry experts, and the use of information in open sources and social media, a study of best practices was conducted and recommendations were developed on the specifics of forming strategies based on sustainable development in war conditions. The object of the study is the strategies of enterprises in the sphere of tourism and recreation in Ukraine.

1.4. The research methodology

The study is based on data from Ukrainian analytical organizations on the role and potential of the tourism industry in the economy, expert assessments of the impact of military operations on tourism and recreation, as well as data from qualitative and quantitative research collected directly from market participants and processed by statistical methods. In addition, in preparing the article, open data was used on successful projects that have been implemented in Ukraine over recent years, including the period of hostilities.

The analysis of the state of the tourism and recreation sector covers 2019-2023, with details on individual important characteristics. The period chosen to conduct an anonymous survey of market participants was November-December 2023.

The scientific novelty of the methodology is as follows: the study of best practices and generalization of successful strategies in combination with desk research made it possible to formulate conclusions about the strategic decisions of tourism companies based on sustainable development

The study found that environmental, social and economic considerations should be seen as a driver of innovation and a source of competitive advantage.

1.5. Paper structure

The current study consists of the following parts:

- firstly, a theoretical basis is provided regarding the formation of strategies in the context of sustainable development;
- secondly, the potential of the tourism and recreation sector in Ukraine is described; analyzed the impact of military operations on the sphere of tourism and recreation; to summarize the impact results, the STEEPLE matrix of external environment analysis was used, quantitative assessments of the influence of individual factors and sub-factors were given; a case analysis of successful practices in the field of tourism and recreation was conducted.
- thirdly, the study of macro environmental factors in combination with the results of case analysis made it possible to highlight the author's recommendations for the development of strategies based on sustainable development, containing a list of possible strategic decisions of tourism market participants, a description of new forms of tourism, as well as the most common digital tools.
- the following are the conclusions of the study on the peculiarities of the formation of strategies in the field of tourism and recreation based on sustainable development in war conditions.

The practical result of the study is that the results can be used as part of the development of strategies by individual market participants to increase their own competitiveness, improve economic and social results, and develop environmental awareness. Researching best practices and disseminating information on the specifics of developing strategies for tourism organizations during the war will allow us to pay focused attention to issues of sustainable development and develop support and recovery programs, including in the post-war period.

2. Theoretical background

In war conditions, when forming a company's strategy, it is necessary to focus on its environmental orientation. Since war destroys the environment, disrupts the natural balance, and negatively affects people's health, the state and enterprises must act to preserve nature and the environment for the future of Ukraine. Environmental orientation in strategy is a set of principles, means and prospects for an enterprise's activities in the natural environment with the aim of preserving it and thereby ensuring its own sustainability.

Ardente et al. [1] note that the main environmental benefits of implementing a green development strategy are the reduction of resource depletion, air emissions and landfilled waste. The proposed strategies are economically viable and reduce costs for the company and have a positive impact on its sustainability.

Beloborodova's [6] proposals regarding the formation and implementation of an environmentally oriented development strategy are worthy of attention. To do this, certain criteria are formed by which the level of environmental responsibility is determined. All criteria are divided into two groups: those that relate to environmental responsibility (i.e., are regulated by law), and those that relate to the enterprise's own environmental initiative and are determined voluntary. The group of criteria for its environmental initiative includes two subgroups of characteristics: environmental management of production and the effectiveness of communications with stakeholders. Forming a strategy for environmentally-oriented development based on these criteria will allow achieving positive changes in the qualitative state of the external environment, improving the quality of final products (services) and the main indicator of the success of this strategy should be the stability of the functioning of the ecosystem.

The priorities for forming a strategy for environmentally-oriented development should be the preservation (restoration) of natural elements of the ecosystem, identifying negative factors that destroy the ecosystem and reducing their influence; restoration and protection of natural resources.

3. Results

3.1. Tourism and recreation in Ukraine

Tourism is considered one of the most profitable sectors of the economy around the world; the tourism industry produces approximately 10-11% of the GDP of countries around the world [7].

Having a favorable geopolitical location, Ukraine has significant recreational potential: favorable climatic conditions, varied terrain, transport networks, cultural heritage. In this context, Ukraine is a rich country bordering the Black and Azov seas, the mountain peaks of the Carpathians and steppe regions inhabited by wild birds and animals. In pre-war times, in 2021, Ukraine entered the ranking of the best tourist countries in Europe.

During the coronavirus pandemic and full-scale invasion, the tourism sector accounted for 2.3% of Ukraine's GDP and provided about 375 thousand jobs [8]. However, the real contribution of tourism to the quality of life and well-being of Ukrainians was greater, because its multiplier effect stimulates spending in related industries: transport, trade, food establishments, etc. This indirect result of the same 2019 amounted to 7% of GDP and 1.2 million jobs [8].

During the COVID-19 pandemic, domestic tourism in Ukraine became more popular. In the post-COVID period, the main destinations for domestic tourism in Ukraine (in percentage) were trips to spas – 44.4, mountain recreation – 29, ski destinations – 19.5, and seaside destinations – 4.1 [9]. It is worth noting that the growing popularity of domestic tourism among the population contributes to an increase in tourist flows, the development of new road routes, the opening of new tourist and hotel complexes and the development of local infrastructure and an increase in local budget revenues, which is particularly important for small towns in Ukraine. In particular, the visibility of local cultural communities is growing.

In February 2022, the war with Russia paralyzed the tourism industry and came to a virtual standstill. The eastern and southern regions of Ukraine have become inaccessible to tourists due to active hostilities, danger to human life, destruction of historical and cultural heritage, systematic shelling and mining of resort areas in the Mykolaiv, Kherson and Odesa regions [10].

3.2. The impact of military operations on tourism and recreation

The scale of the impact of military operations on Ukrainian tourism is still difficult to fully assess, because a full-scale war continues. However, it is already known that in 2023 tourism enterprises decreased by 36% compared to 2021 [8]. Russian occupation, military operations and constant shelling of different regions lead to the destruction of infrastructure: hotels, recreation centers, airports, railway connections, as well as museums, historical attractions, nature, that is, what people travel for (if we are not talking about work trips). Significant territories in the east, south and north of Ukraine are mined. According to foreign experts, this is about 30% [8] of the entire area of the country. It is even more difficult to assess the long-term impact of the war on the country's tourism potential, because while the world will associate Ukraine with destruction and grief, the challenge will be to convince the international community of its safety and reliability for tourism and investment.

According to the Ministry of Environmental Protection and Natural Resources, according to preliminary estimates, as of March 1, 2022, the aggressor was conducting military operations on the territory of 900 objects of the natural reserve fund with an area of 12,406.6 square kilometers, which is about a third of the area of the natural reserve fund of Ukraine [11]. About 200 Emerald Network sites covering 2.9 million hectares are under threat of destruction. The Emerald Network is a network of protected areas created to conserve species and habitats that are in need of protection at the European level but are located in non-EU countries. These are habitats for thousands of species of plants and animals. These areas play an important role in protecting biodiversity and preserving the climate. The habitats of some rare and endemic species and habitats have been affected by the active hostilities, which threatens their existence, such as virgin, uncultivated steppes, chalk slopes in Donetsk region, coastal habitats in the southern regions, and marshes in the north. As a result of the hostilities, part of the forests in Luhansk, Donetsk, Zaporizhzhia and Kherson regions are currently under the control of the occupiers [11].

The fact that Ukraine is in a state of war presents new challenges for the development of tourism, which are complicated by a number of problems, namely: zones of occupation and active military operations are dangerous for tourists; loss of a significant part of the natural, historical and cultural potential of tourist areas; destruction of tourism infrastructure; decreasing savings for vacations; violation of logistics within Ukraine; departure of the working population abroad, etc [10].

Tourism in Ukraine is losing a very significant amount of finance. Firstly, this is due to a decrease in the total number of tourists. There were about 4 million foreign tourists in 2020, almost 90 thousand of them used the services of Ukrainian travel agencies. In 2022-2023, this figure decreased fourfold. The situation is quite similar with domestic tourism. Due to active hostilities, threats of missile strikes and mined tourist areas, 13 of 24 regions were left largely without tourism [12].

As of June 2023, the share of direct damage caused to the infrastructure of the spheres of culture, religion and tourism is $2.4 billion. In total, since the beginning of the war, at least 1,804 cultural sites, 348 religious buildings, 343 sports sites, and 164 tourism sites have been damaged or destroyed. Total indirect losses in the spheres of culture, tourism and sports as of June 2023 amount to $10.8 billion, of which $6.4 billion are culture and sports, $4.4 billion are tourism [12].

3.3. Recommendations for developing strategies based on sustainable development

3.3.1. STEEPLE analysis of the external environment. An important stage in the formation of a strategy is to determine the state of the external environment of the company's functioning. The STEEPLE analysis method allows one to describe the components of the external environment, have a positive and negative impact of these factors on the development of companies in the industry being studied, and determine the strength of this influence using expert advice. Table 1 shows the results of the STEEPLE analysis of factors influencing the activities of companies in the tourism sector. The analysis methodology involved the authors formulating the content and characteristics of individual subfactors and their subsequent assessment by market participants. The survey was conducted in November 2023 and included 33 respondents representing companies operating in the tourism and recreation sector. Research has shown that the greatest influence is exerted by economic factors of the external environment (table 1).

Table 1: Factors of the external environment according to the STEEPLE analysis matrix.

Group of factors	Manifestation of the factor	Nature of the influence	Strength of influence
Economical	Reduction in market capacity as a result of a significant number of the population (citizens) leaving abroad, changing priorities, falling solvency and general instability.	−	9.7
	Infrastructure in many regions has been destroyed and damaged: airports, roads, bridges, hotels and other recreational and tourism facilities.	−	8.0
	Many accommodation establishments were forced to close due to safety concerns, lack of demand, and technical reasons.	−	8.0
	The current situation has resulted in a change in the quality of tourist flows.	+	5.7
	Changes in tourist routes as a result of military operations, especially in border areas.	−	5.7
	Transformation of international business tourism into volunteer and solidarity tourism.	+	5.7
	Reorganization and change in business strategies of market participants.	+	7.3
	Development of the tourism potential of regions of Ukraine remote from the combat zone.	+	9.0
	Development of new forms of financing socially important and environmental projects.	+	6.3
Political	The hostilities have led to increased instability and security threats, which has influenced tourists' decisions to visit the country.	−	9.7
	Occupation and replacement of part of the territory of Ukraine, threats of missile attacks and airstrikes.	−	9.3

Continued on next page

Table 1 – continued from previous page

Group of factors	Manifestation of the factor	Nature of the influence	Strength of influence
Social	Boarding houses and hostels were used as temporary shelter for displaced people forced to leave their homes due to fighting.	+	6.3
	The war stimulated the development of domestic tourism in Ukraine. Numerous Ukrainians decided to visit and support the country during this difficult time.	+	7.7
	In some regions, tourism is also facing an outflow of personnel. Due to the difficult situation, employees are looking for work in safer areas or near the border.	–	6.0
	Development of cooperation with local authorities, partnerships at the regional level to better take into account the characteristics of the territory.	+	5.7
	Development of volunteerism, mutual support, civic consciousness, implementation of donation-based restoration projects, acquisition of social connections, improvement of the level of interaction between the state and citizens.	+	6.3
Technological	Development of virtual tourism in Ukraine. Inviting tourists to virtual excursions or online tours.	+	5.7
	Using digital tools to promote projects and services: extensive data analytics, geoanalytics, targeted advertising, development of online services, special services and applications.	+	5.0
Legal	Since the full-scale invasion, Ukraine has been subject to a wartime legal regime and associated risks, such as curfews, restrictions on visiting certain locations, filming bans, etc.	–	7.7
	The war stimulated the development of domestic tourism in Ukraine. Numerous Ukrainians decided to visit and support the country during this difficult time.	+	7.7
Ethical	The massive media campaign on the war in Ukraine is reflected in the image of the country.	–	5.3
	The ethics of competition acquires specific features: as a result of destruction, environmental disasters, and the loss of specialists, some travel companies disappeared from the market.	+–	5.0
Environmental	Changing the landscape of tourist sites. The military conflict led to the destruction, occupation or change of territorial affiliation of many popular tourist sites.	–	5.0

Continued on next page

Table 1 – continued from previous page

Group of factors	Manifestation of the factor	Nature of the influence	Strength of influence
	Direct harm to the environment caused by the physical destruction of objects, the appearance of additional garbage, emissions, etc.	–	6.3
	Growing environmental consciousness of tourists. They have become more aware of the environmental impact of their travel and are looking for ways to travel more sustainably.	+	6.7

The most influential economic factor of negative impact is the reduction in market capacity as a result of the departure of a significant number of the population (citizens) abroad, changes in priorities, a drop in solvency and general instability. In general, for the group of economic factors, the impact is estimated at 65.4 points. The overall influence of political factors is determined at 19 points, social – 32 points.

The generalized influence of macroenvironmental factors is presented in figure 1.

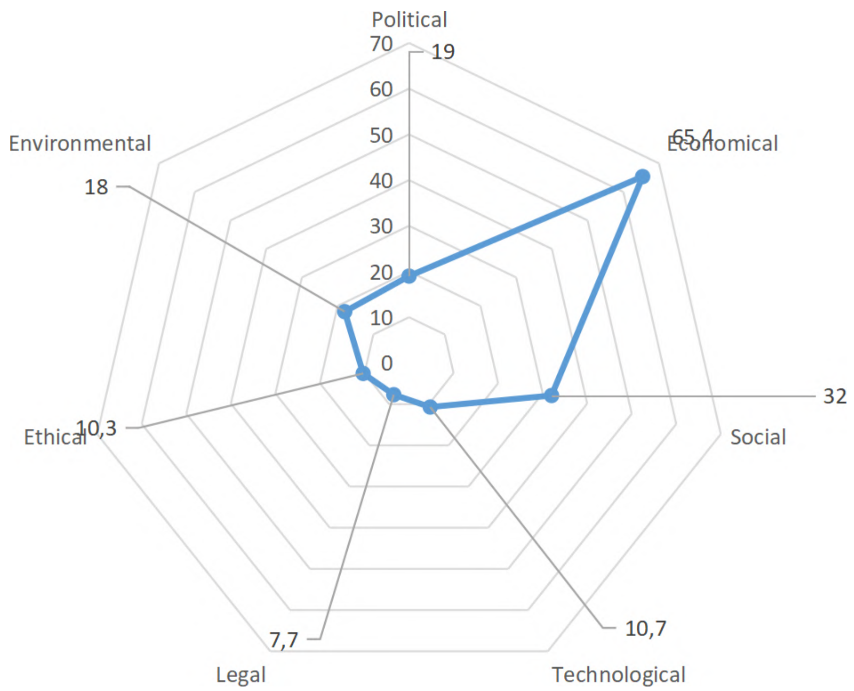

Figure 1. STEEPL analysis of marcoenviromental factors.

The resulting diagram shows the greatest influence on the activities of travel companies by economic, social, political and environmental factors. Accordingly, when forming a company's development strategy, they should be taken into account first.

3.3.2. Case analysis of successful practices in the field of tourism and recreation. In our study, we analyzed five tourism projects and described the unique experience of these companies in successfully operating during war.

The Potter's House is a family business run by Olha and Oleh Pavlik, which has been operating in the Ethnoselo cultural and tourist complex in Zaporizhzhia Oblast since 2015. They organize pottery masterclasses, welcome guests and conduct excursions. When the war broke out, Olha became the coordinator of the complex and provided shelter to 600 people fleeing the war from the Zaporizhzhia region. The Ethnoselo also helps people with disabilities by employing them and developing a park where young people recycle waste. There is a special swing for people in wheelchairs. At the beginning of the full-scale war, the Potter's House won a grant to support people with disabilities and developed the brand "Fitochai". The project involves people with disabilities collecting medicinal herbs, drying them, packaging them and selling them as tea from the Zaporizhzhia steppes. Now the Potter's House already has a small plantation and a greenhouse with medicinal plants. The highlight of the complex is the upcycling park, where garbage is recycled, and new items are made from used items. Most often, we work with beverage bottles and plastic sets, reducing them to make them easier to transport to collection points. This is also a social project involving people with disabilities. Since children in wheelchairs often came to the complex, we created a swing that a child can use to swing in a wheelchair [13].

When Oleg Pavlik returned home with a wound, it became clear how important rehabilitation is for the military. Therefore, it was decided to create a rehabilitation center to support military personnel and family members. Now Oleg Pavlik is interested in beekeeping, so the company plans to make a house for apitherapy, which will help military personnel after injury and veterans improve their emotional state [13].

The Shelter Project is the largest service aimed at finding free housing for Ukrainian refugees and internally displaced persons who suffered losses as a result of the full-scale war in Ukraine, both within the country and abroad. This government project is run on a volunteer basis and aims to promote connections between those in need of shelter and those who are willing and able to provide it. Participants in the program providing shelter to internally displaced persons (IDPs) receive compensation from the state, observing the main condition – to provide housing free of charge. As of January 2023, approximately 16 thousand advertisements are available on the web platform, of which 13 thousand are located in different regions of Ukraine, and 3 thousand are located abroad. The site offers translation of texts into 40 languages [14].

The Flat Planet [15] project is an innovative travel app whose main goal is to provide excursions around the world, particularly as an alternative to traditional tour guides. The concept of this startup, according to its founder Dmitry Dubilet, arose during the global COVID-19 pandemic, when restrictive measures were introduced, but it is noted that today this project is quite relevant for Ukrainian users. The app's audio content plays based on geographic coordinates and is available in different languages. Flat Planet also offers collaborations with cultural institutions and tour guides to produce content for visitors. In this case, identified users can determine whether to make the content paid or free, and the resulting income in the amount of 100 % is transferred to the museum. Flat Planet's plans include launching online excursions both within Ukraine and abroad.

The pandemic became a decisive factor for the launch of the tourist and recreational complex ULIS, founded by Ukrainian businessmen Evgeniy Lavrenyuk and Igor Farberov with the aim of providing ecological recreation in the middle of the forest, without any territory restrictions or fences. A special feature of this project is the absence of a single investor, allowing everyone who shares these values to join its development and become an investor.

During the full-scale war, the ULIS project consisted of 27 permanent houses in the Kyiv region. However, during the invasion of Russian troops in February 2022, the community where the houses are located found itself under occupation. Although properties are intact, confidence in investing in the region has dropped significantly. The founders of the ULIS project solved this issue by developing cabins – portable ecological houses that can be moved.

The main goal of the ULIS project is to develop environmental consciousness and support the society where it is implemented. Ten percent of the profits from ULIS are allocated to social initiatives within the local community, such as creating walking paths in the forest adjacent to the hotel location, repairing roads damaged during the occupation, financing social infrastructure and sorting waste. The founders of the ULIS project are also developing a social complex in the city of Khust in the Transcarpathian region, aimed at providing housing for internally displaced persons based on the reconstruction of a mothballed hotel building. The main goal of this project is to provide housing for internally displaced persons. When booking for a long time, hostel rooms were given at cost, but in the end they settled on a model in which housing is provided free of charge thanks to donations from philanthropists [16].

Volunteer tourism became an important component of tourism activities during the war. Public organizations (such as "Brave to Restore" and "BUR-Camp") are active participants in volunteer initiatives aimed at restoration and rehabilitation in de-occupied territories. The work is carried out through donations from Ukraine and abroad. Foreign volunteers also show interest in restoration, most of whom are visiting Ukraine for the first time [17].

The "BUR-Camp" project is a volunteer construction camp operating in different cities and villages of Ukraine, attracting young people from all over the country to volunteer. Here, volunteer participants repair houses for people who have lost their homes due to war, restore buildings damaged during shelling, and contribute to the creation or improvement of youth centers. In addition, volunteers can discover a new area, gain new knowledge, have fun and establish social connections [18].

In addition to the above-mentioned cases, it should also be noted that in Ukraine for a long time there have been various veterans' institutions, the basis of which is the reintegration of former military personnel into civilian life. However, with the beginning of the full-scale invasion, tourism institutions also became involved in this process. One of these projects was the city program for the socio-cultural rehabilitation of military personnel who are being treated or undergoing rehabilitation in medical institutions located on the territory of the Lviv city territorial community. The essence of the project is to organize excursions for veterans and injured military personnel. For the military, such measures are a way of adapting to civilian life after hostilities [19].

3.3.3. Strategic development toolkit. The study of successful practices and cases of domestic entrepreneurs made it possible to formulate a list of possible strategic decisions of tourism market participants, formed on the basis of the components of sustainable development (table 2).

Table 2 presents strategic decisions that travel companies can make depending on the situation in the business environment and taking into account the entrepreneurial potential of a particular travel company.

3.3.4. New formats of Ukrainian tourism that emerged or spread during the war. During the war, new functions arose in Ukraine: volunteer assistance and humanitarian support; "solidarity tourism", there has been a shift in emphasis – from entertainment to restoration; investing efforts in the integration of temporarily displaced persons, searching and developing common values

The inclusion of these types of services in the activities of tourism and recreation enterprises can bring additional value to consumers and thus increase the competitiveness of market participants. It should also be noted that the above services correlate with the ideology of sustainable development, since they are focused on ethical and social phenomena. Taking into account the needs of Ukrainian citizens for such new types of services in war conditions will allow us to develop public values of mutual support and respect for new requests from consumers (table 3).

Table 2. Strategic decisions (efforts) of tourism companies based on sustainable development.

Economic	Social	Environmental
• Job creation • Investing in security: availability of shelter, backup power sources, water, communications • Development of online services, virtual tourism, digital platforms, innovative applications • Entering international markets	• Creation of rehabilitation conditions for military personnel, members of their families and other citizens of Ukraine • Support for inclusion • Development of volunteer, memorial and solidarity tourism • Implementation of projects to preserve the cultural heritage of Ukraine	• Initiation of waste processing and disposal projects • Development of environmental consciousness, ecological and cultural tourism

Table 3. Types of services related to sustainable tourism.

No.	Types of services	Description
1	Memorial tourism	Documenting the consequences of Russia's armed aggression against Ukraine
2	Solidarity and volunteer tourism	Combination of tourism and volunteering to support and quickly restore de-occupied territories
3	Inclusive and recreational tourism	Providing tourist services for military personnel and their families, as well as other categories of people affected by hostilities
4	Ecological tourism in Ukraine	Preference for quiet places where you can enjoy nature and take a break from the bustle of the city

3.3.5. Elements of digital strategies. Analysis of the strategies of market participants showed that they widely use innovative digital tools, the main ones of which are presented in the table 4.

In general, tourism in Ukraine today is effectively adapting to new conditions. Despite the war, Ukrainians continue to discover its natural and cultural diversity.

The environmental consciousness of tourists has increased significantly. They have become more aware of the environmental impact of their travel and are looking for ways to travel more sustainably. Businesses offering environmentally friendly goods, services or eco-tours have become more popular and attractive to tourists.

4. Conclusions

In general, tourism is an important sector of the Ukrainian economy. It is a source of cash income and also actively contributes to the creation of new jobs. The tourism and hotel sectors are one of the most dynamic sectors of the Ukrainian economy, which, despite all the difficulties and challenges that Ukrainians have to face, continue to develop in an amazing way.

The Ukrainian tourism industry needs flexibility, creativity and cooperation of all participants in this market to ensure its stability and development. Tourism in Ukraine faces many obstacles,

Table 4. Digitalization tools in tourism.

No.	Digitalization tools	Description
1	Big Data analytics	Organizations use this technology in the areas of customer service, operational efficiency, and risk management.
2	Geoanalytics	For the successful development of this business, it is important to understand where the flows of tourists are coming from and where they are going. And geo-analytics is key to understanding trends.
3	Targeted travel offers	Thanks to modern technologies, tourism has received a number of effective tools to attract audiences. So, let's say, it is possible to offer services based on an analysis of preferences, habits, and experience.
4	Virtual tourism	Tourist requests for virtual excursions or online tournaments could be an alternative for those who are not ready to alienate the country especially.
5	Expansion of online services	Booking tours, hotels, purchasing tickets, obtaining a green card and health insurance, 24-hour support for tourists who need help. Providing MTPL and health insurance.
6	New travel apps	With excursions around the world, which are designed to become an alternative to guides. The audio content of the application is played in relation to geocoordinates and is available in many languages.
7	Online platforms	For volunteering, mutual assistance, finding partners, financing, information exchanges, popularizing projects.
8	Cultural Digitalization	Digitization and cataloging of museum and cultural exhibits to preserve cultural heritage and make online exhibitions available to the public.

but it has already demonstrated incredible resilience and enormous potential. And despite external and internal obstacles, the tourism business continues to look for ways to adapt and innovate. At the same time, the development of tourism in Ukraine requires joint efforts from the government, business and the public. Indeed, with the right approach and strategy, Ukraine will be able not only to restore its tourism potential, but also to strengthen it, attracting tourists from all over the world with its unique culture, nature and hospitality. Moreover, tourism in Ukraine after the war is predicted to become a promising niche for small and medium-sized businesses.

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Concept of synthesis of the digital twin of the rock massif based on the stability criterion

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Concept of synthesis of the digital twin of the rock massif based on the stability criterion

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Abstract. The proposed concept of synthesizing the digital twin of a rock massif is based on the application of a developed method for determining stability coefficients. This method involves measuring the intensity of electromagnetic pulse (EMP) in rock formations and application of Intelligent AutoRegressive Moving Average with Bumpiness and Sparsity regularization (ARMABiS) system. ARMABiS is a modification of the Wang-Mendel fuzzy neural network designed for field processing of primary information regarding the transient process of EMP intensity before, during, and after a mass explosion in a quarry. The reconstruction of the spatial field of stability criteria for the rock massif along the quarry perimeter is also considered. The uniqueness of the method lies in the prior determination of the frequency range corresponding to the specified depth of the rock massif to assess the stability reserve coefficient. Explosions during rock blasting are used as an external influence on the massif. The method involves measuring the parameters of the transient process through electromagnetic pulse impulses during mass explosions and until the restoration of the background EMP level. The stability reserve coefficient of the massif is determined by a formula that considers the internal friction angle of rock formations, the maximum value of EMP induced by the explosion, and the duration of damping to the background EMP level

1. Introduction

Ensuring the stability of quarry slopes is one of the key challenges in mining engineering and geomechanics. Over the past decades, with the increase in depth and intensity of excavation in quarries, the importance of a reliable assessment of slope stability has significantly grown. A crucial indicator in this context is the safety factor of the rock mass, defined as the ratio of the actual strength of the rocks to the applied loads. The relevance of this problem is emphasized in the works of many scientists and researchers, such as Toderaş and Filatiev [1], where particular attention is given to the development and adaptation of stability assessment methods to the specific conditions of quarries in different regions.

Modern methods for assessing the stability of quarry slopes are based on a comprehensive approach to analyzing the geomechanical characteristics of rock formations and their spatial arrangements. As indicated by Adriansyah et al. [2], important factors in this process include the geological structure of the massif, the physico-mechanical properties of rocks, the presence, and characteristics of fractures, as well as hydrogeological conditions.

One of the most widespread and traditionally used approaches to stability assessment is the limit equilibrium method, detailed in [3]. This method allows for evaluating the conditions for potential slope failure based on the analysis of force equilibrium in the rock mass. However, as noted by [4], this method has its limitations, especially in conditions of complex geological settings.

In recent years, numerical methods such as the finite element method and the discrete element method have gained popularity. These methods, discussed in [5, 6] enable a more accurate and detailed analysis of the stress-strain state of rock formations, considering their heterogeneity and anisotropy. The assessment of quarry slope stability and the determination of the safety factor of the rock mass are fundamental tasks in mining engineering [7], aimed at ensuring the safety and efficiency of mining operations. The significance of these studies is justified by the potential risk of collapses, which can lead to significant economic losses and, more importantly, pose a threat to human life.

The safety factor, a key indicator in the assessment of the stability of rock masses, is determined as the ratio of the actual strength of the rock to the loads acting on it. This indicator helps experts assess the potential danger of slope failure and develop appropriate measures to reinforce quarry slopes. Major methods for slope stability assessment include the limit equilibrium method, finite element method, finite difference method, and discrete element method, each having its advantages and application areas depending on the specific conditions and characteristics of the quarry.

Currently, there is a known seismic-acoustic method for predicting massif stability, involving the registration and analysis of acoustic emission impulses. However, a drawback of this method is its limited application, as the use of piezoelectric geophones does not account for geomechanical processes accompanied by compression or extension of the rock mass, determining its deformation.

Applying the borehole methodology for determining the stability of rock mass sections requires drilling boreholes in the research areas, which is not always technically feasible [8]. This complicates the measurement of acoustic emission, considering which stability assessment of the massif is conducted.

The most technically relevant and results-oriented approach to the developed methodology is the method for determining the safety factor of the massif based on the magnitude and frequency of acoustic emission impulses. This method is based on the registration of acoustic emission impulses occurring in the investigated massif during the drilling process and determination. A disadvantage of monitoring acoustic emission impulses is that, in this method, it is possible to measure acoustic emission only in the immediate vicinity of the drilling site, negatively affecting the relevance of determining the safety factor reserve of the rock mass [9].

The aim of this research is to increase the accuracy of determining massif stability by measuring electromagnetic pulse impulses simultaneously over significant areas. This is achieved by considering the time of the transient process until the restoration of the natural EMP background, allowing for the consideration of stress concentration in rock mass locations with different types of heterogeneity, such as fractures, inclusions, etc.

2. Methodology

The goal is achieved in the developed methodology for determining the safety factor of rock mass stability, involving the measurement of EMP magnitudes in the massif of rocks arising from natural stresses in the massif and additional loads added to it. Explosions during ore blasting are used as additional loads to excite EMP in the massif. The time of EMP damping after ore blasting until returning to the background EMP level is measured, and the safety factor of massif stability can be determined by the formula [10]:

$$Y_c = \tan^2 \phi \left[\left(e^{-0.01m} + e^{-0.02m} + e^{-0.03m} \right) + \left(e^{-0.01t} + e^{-0.02t} + e^{-0.03t} \right) \right] \tag{1}$$

where ϕ is the internal friction angle of rock formations, degrees; m is the maximum EMP intensity induced by the explosion, impulses per second; t is the duration of damping to the background EMP level, seconds.

Measurements of acoustic emission intensity arising from natural stresses in the rock massif and additional loads are conducted in the rock mass. The stability of the massif is assessed based on the parameters of acoustic emission impulses, and the coefficient of friction of rock formations is preliminarily determined. Explosions during ore blasting are used as additional loads to excite EMP in the massif. The time of EMP damping after ore blasting until returning to the background EMP level is measured, and the safety factor of massif stability can be determined by the formula (1).

During the first stage, the background EMP value is measured before ore blasting. Then, measurements and recording of EMP magnitude are carried out directly during the explosion and throughout the transient process after the explosion of rock formations [11]. Simultaneously, the time from the moment of the explosion to the restoration of the natural EMP magnitude background is measured and recorded for depths of 300-400 meters in the frequency range of 0-1 kHz, and for depths up to 80 meters in the frequency range of 1-2 kHz.

In the initial period after the explosion, the EMP magnitude will be significantly higher than the natural background before the explosion. Over time, EMP will decrease and reach a constant value of the natural background. The natural EMP background after the explosion in a stable rock massif will be lower after some time, due to the redistribution of stress in the massif. In an unstable massif, EMP will generally be higher, as explosions in unstable rocks induce intensive stress redistribution in the massif.

Based on the conducted measurements, the maximum intensity of EMP (m) is obtained, and the time of damping of peak EMP values to the background level (t) is determined. The safety factor of rock mass stability is calculated using the formula:

$$\text{If } Y_c > 1, \text{ the massif is stable.}$$
$$\text{If } Y_c < 1, \text{ the massif is unstable.}$$

Thus, by combining new and known features, the reliability of determining massif stability is increased by the ability to measure electromagnetic pulse impulses simultaneously over large areas and by selecting the frequency range for different depths of the rock mass when determining the safety factor of stability.

3. Results and discussion

The chosen object of study is the Velyka Hleyuvatka deposit located in the Kryvyi Rih iron ore basin. In this basin, three structural-tectonic zones are distinguished: Southern, Saksahansky (Central), and Northern.

The Velyka Hleyuvatka deposit is associated with the Southern part of the Saksahansky zone and is located in its thrust part. The characteristic feature of the rocks of the Kryvyi Rih series, which constitute the deposit, is the monoclinal steep bedding with a western dip at an angle of 40-55º and a north-northeast strike at an angle of 20-25º.

The most significant tectonic disturbance in the Velyka Hleyuvatka deposit is the Saksahansky thrust, which extends throughout the Saksahansky belt and is represented by several zones of complexly foliated structure. The thrust plane dips at an angle ranging from 9º to 32º to the south-west on the north-east [12].

Within the deposit, several diagonal faults are traced, branching off from the Saksahansky thrust. These faults are of the strike-slip type with a variable azimuth ranging from 20-30º to 300-310º. The dip of displacement planes, typically, is to the east at an angle of 30-45º, but with depth, the dip angle increases to 65-80º.

In the southern part of the deposit, several sub-latitudinal faults of the strike and strike-slip type are observed. The dip of displacement planes is towards the east at an angle of 65-90º [13].

At the boundary of the quarry's sanitary protection zone (figure 1), the natural background EMP of the rock massif was measured at the first stage (points 1, 2). It amounted to m1 = 10-14 impulses per second. In the next stage, measurements were taken immediately after the explosion of the rock formations until the restoration of the natural background (figures 2, 3).

Figure 1. Layout of measuring equipment stations in the plan of the area adjacent to the quarry.

After the explosion on August 3, 2023, the maximum intensity of EMP was $m_2 = 140$ pulses per second. The natural background was restored after $T = 37.200$ seconds. The internal friction angle of the rocks in this area was $\phi = 41^\circ$. According to the expression [1], the stability reserve coefficient of the massif was determined, which equaled 0.241. The calculated stability reserve coefficient is less than one, indicating instability of the massif. The advantages of the developed

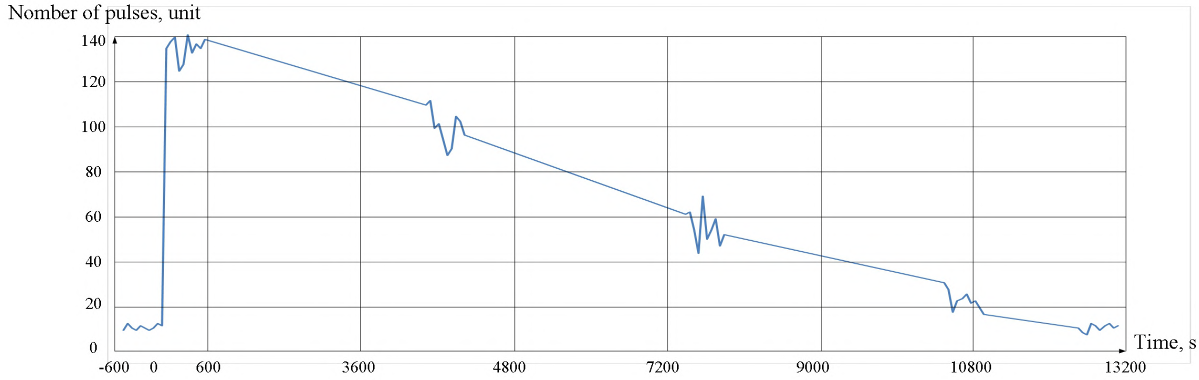

Figure 2. Results of EMP pulse measurements before the restoration of the normal EMP background at measurement point 1.

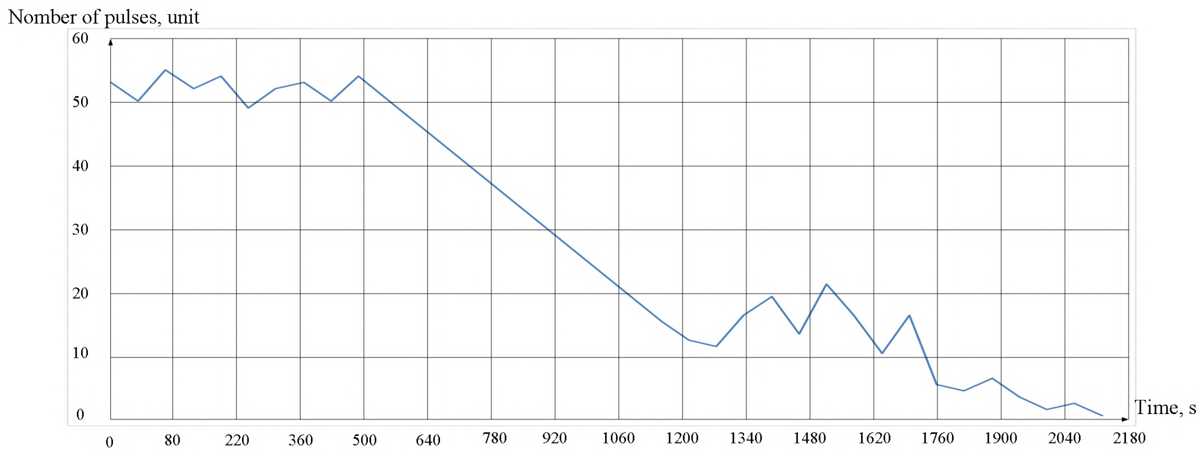

Figure 3. Results of EMP pulse measurements before the restoration of the normal EMP background at measurement point 2.

methodology lie in the increased reliability and accuracy of determining the stability reserve coefficient of rock mass areas. This allows for a more reliable assessment of the likelihood of sudden rock mass collapses, evaluation of the results of measures aimed at increasing the stability of massifs, and more accurate determination of mining operation regimes. This is crucial for ensuring safe working conditions and preventing injuries.

After the explosion on March 30, 2023, the maximum intensity of EMP was $m_2 = 55$ pulses per second. The natural background was restored after $T = 2.100$ seconds. The internal friction angle of the rocks in this area was $\phi = 45°$. According to the expression (1), the stability reserve coefficient of the massif was determined, which equaled 1.102. The calculated stability reserve coefficient is greater than one, indicating stability of the massif.

4. Mathematical foundation for the synthesis of the digital twin of a mining massif (ARMABiS) based on stability criteria

Considering that the measured Electromagnetic Pulses (EMPs) are derivatives of natural stresses in the massif and additional loads induced by mass explosions, the creation of a digital twin for a mining massif based on stability criteria involves conceptualizing the synthesis of this intelligent autoregressive structure with regularization. In this context, the overall adaptation process of the digital twin will be implemented as a function of several variables, in which one or more variables have predefined stability criteria for the mining massif.

In accordance with the foregoing, the dynamic model for the digital twin of a mining massif will employ the developed structure of the adaptive AutoRegressive Moving Average (ARMA) model with distributed lag [14] The model is dynamic, where criterion lags are utilized as regressors.

The general form of the model with distributed lag (ADL(p,q) – Autoregressive Distributed Lag) is presented below:

$$y_i = \alpha + \sum_{k=1}^{\rho} \beta_k Y_{i-k} + \sum_{j=0}^{q} \gamma_j X_{i-j} + \varepsilon \tag{2}$$

where α is the model constant; β is the autoregressive coefficient; y is the distributed lag coefficient; ε is the model error.

The first sum represents the AutoRegressive (AR) component in the form of a distributed lag of the criterion variable, and the second sum represents the distributed lag of the regressor. In the operator form, the ADL(p,q) model takes the following expression:

$$y_i = \alpha + Bf(B)y_i + g(B)x_i + \varepsilon \tag{3}$$

where $f(B)$ and $g(B)$ are polynomials.

The difference equation (3) characterizes autoregressive processes (AR(p) model with a distributed lag of the criterion parameter) with a moving average (MA(q) model with a distributed lag of the regressor), or ARMA processes. Let's express the discrete ARMA model with a distributed lag of order (0,q) (MA(q)) for the reference stability criterion (desired):

$$y^*[i] = \alpha + \sum_{j=0}^{q} \gamma_j x[i-j] + \varepsilon \tag{4}$$

At the same time, the final difference of the second order of the output coordinate will have the form:

$$\Delta^2 y[i] = 1 - 2B + B^2 = \mu(y^*[i] - 2y[i-1] + y[i-2]) \tag{5}$$

where μ is the adjustment speed.

By excluding the measured quantity (EMP) from the last equation, we obtain the discrete ADL(2,2) model characterizing the ARMA process:

$$y[i] = \mu y_0 x[i] + \mu y_1 x[i-1] + \mu y_2 x[i-2] + (1-\mu)2y(t-1) + (\mu - 1)y[i-2] + \mu\varepsilon \tag{6}$$

In order to imbue intelligent properties to the ADL models, an adaptation method for weight coefficients $y_0, y_1, y_2 ... y_n$ has been developed based on a modified gradient method for minimizing the quadratic functional. This method serves as the foundation for adjusting the weights of the Wang-Mendel fuzzy neural network [15].

$$J(\varepsilon_u) = 0.5\varepsilon_u^T \varepsilon_u \tag{7}$$

As there is no explicit dependency of the vector (as per components (6)) and the function $J(\varepsilon_u)$ on the weight coefficients $y_0..y_l$, the error ε_u in the adaptation procedure of the fuzzy neural network (5) is recalculated into generalized errors , which explicitly depend on the values of $y_0..y_l$. In this case, the adaptation of the weight coefficients of the digital twin of the rock mass (5) at the step $[i+1]$ is carried out according to the following pattern:

$$\gamma_j[i+1] = \gamma_j[i] - \lambda q^{(i-j)}[i]\Lambda^{(j)}[i] \tag{8}$$

where $q^{(i-j)}$ is the distributed lag of the regressor or the criterion parameter.

$$\Lambda^{(j)}[i] = \mathrm{col}\left(\frac{\partial J}{\partial q_1^{(i-j)}}, \ldots, \frac{\partial J}{\partial q_{n_j}^{(i-j)}}\right) = -\varepsilon_u[i] \tag{9}$$

Therefore,

$$\gamma_j[i] = \gamma_j[i-1] + \lambda \cdot \varepsilon_u[i] \cdot q[i-j-1] \quad \text{for } j = 0, 1, \ldots, \ell, \lambda > 0 \tag{10}$$

The adaptation error $\varepsilon_u[i]$ is defined as the difference between the measured stability coefficient and the actual output of the digital model (stability coefficient of the rock mass) at the i-th iteration.

It is necessary to note that the task of determining the lag structure of ADL(p,q) models (2) is solved according to the developed method [16] for estimating the value of the maximum lag, which is based on the analysis of finite differences of the transient function of the digital model of the rock mass.

5. Conclusion

As a result of industrial research conducted at the quarry of Joint-Stock Company Yuzhniy GOK dependencies of the frequency ranges of the Earth's electromagnetic field on corresponding depths of rock stability studies have been confirmed. Specifically, for depths of 300-400 m, the informative frequency range is 0-1 kHz, while for depths up to 80 m, it is the frequency range of 1-2 kHz. Scientific conclusions have experimentally confirmed that the intensity of electromagnetic pulses is derived from natural stresses in the array and external disturbing influences in the form of mass explosions from rock rebounds.

Additionally, it has been experimentally verified that the portrait (parameters) of the transient process for EMP from a mass explosion allows for the determination of the stability margin coefficient of the rock mass.

The results of the study on the possibility of synthesizing a digital twin of a rock mass based on the stability coefficient, through the development of an intelligent autoregressive system with regularization, which is a modification of the fuzzy neural network of Wang-Mendel, led to the following conclusions:

- the proposed method for constructing a digital twin of a rock mass allows solving problems related to determining the stability of quarry walls when EMP is measured at only one control point within the calculation sector;
- the proposed system operates under conditions of previously designed measurement sectors for EMP;
- the proposed synthesis method allows for the creation of digital models for quarries without a mathematical description of the distribution of the stability coefficient along the quarry walls;
- the structure and algorithm of operation of the developed system are oriented towards functioning in conditions of errors in determining the parameters of the EMP transient process, which are not subject to operational control;
- the formation of basic transformation laws of the model can be carried out taking into account the availability of a priori information;
- the process of primary adaptation of the parameters of the digital twin of the rock mass takes place over two periods of primary EMP measurements at each control point in the sector.

In the presence of significant errors in EMP measurements, the developed intelligent system requires 3-4 periods to stabilize an adequate level of system error based on the stability criterion throughout the rock massif. This can be explained by the functional features of fuzzy reasoning technology.

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Study and analysis of amber deposits using ArcGIS techniques

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Study and analysis of amber deposits using ArcGIS techniques

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Abstract. Amber deposits are located within the Baltic-Dnipro province and cover vast land areas and coastal seas. In the regional dimension, the formation of amber deposits is determined by the climatic, facial and tectonic features, so it is important to link their occurrence to specific structures, especially on platform areas where morphostructures are linked to the tectonic structure. Amber deposits on the territory of Ukraine are considered to be non-commercial due to their low technical and economic indicators and limited geological exploration. The evaluation of amber deposits is proving to be an important task that affects the country's economy. The question of the origin of known placers, including intermediate collectors, remains unresolved. Numerous researchers studied amber placers, however, the question of the origin of placers, methods of their detection and evaluation is still relevant at the present stage, since the solution of this issue will largely allow to revise their resource potential. This article examines the prospects of utilising the ArcGIS geographic information system to analyse the geological and economic potential of amber resources in Ukraine. Geological and economic modelling using ArcGIS tools makes it possible to determine the industrial value of exploration of amber deposits. The calculation of the geological and economic indicators of the deposit is based on the most relevant data under current conditions.

1. Introduction

Amber placers belong to deposits of a very complex geological structure with variable quantitative or qualitative parameters of deposits and extremely uneven nested distribution of amber in terms of sediment thickness and area of their development [1]. Their boundaries are defined only on the basis of sampling data. Placers are controlled by palaeogeographical factors and the possibility of predicting and extrapolating the placer is complex.

On the territory of Ukraine, amber deposits are represented by placers associated with the Carpatian province and the sediments of the Prypiat and Dnipro basins of the Baltic-Dnipro Amber Province. Commercial amber deposits in the Prypiat basin are associated with sediments of coastal and marine lagoon-deltaic facies [1]. Marine lagoon-deltaic deposits, which are widespread, are the main geological and industrial type of fossil resin deposits not only in Ukraine, but also in the USA, Canada, Burma, etc.

Geological exploration of amber deposits is directed towards determining the material composition, quantity, quality and processing properties of amber, geological structure, hydrogeology, mining and other conditions of deposits, for further substantiation of engineering solutions on the method and system of extraction and the scheme of integrated processing of ore materials. The techno-economic study of amber deposits is aimed at establishing, in ever-increasing detail, the mining engineering, geographical-economic, socio-economic, economic and other conditions for the industrial development of the discovered ore deposits, suitable extraction methods and technological schemes of mining [2].

These tasks are successfully solved by GIS. As for the distribution of geological, mining and economic indicators for amber deposits, Polish researchers have developed considerable experience [5]. However, an important aspect of research here is the development of a geological and genetic model of the deposit, since amber is characterised by complex patterns of accumulation in traps due to its low density and ability to move in different ways: by saltation, floating on the water surface, in suspension, depending on many factors. That is why the patterns of amber placer formation differ from those of heavy minerals. Hence the complex distribution of amber concentrations in deposits.

According to Czuryłowicz and Sałaciński [3], amber is transported mainly in a suspended state, with only large pieces being subject to drag. In flowing aquatic environments, amber is deposited in places where the near-wall layer of the current is detached from the substrate, i.e. in various depressions in the riverbed over which the current is slowed down, for example, in depressions on the underside of ledges. In other words, we are dealing with geomorphological and sedimentary traps. Amber deposition in deltaic sediments occurs in the subaquatic part, within the sedimentary strata of the prodelta and adjacent embankments of distribution channels. Wave action, the nature of the currents, the distribution of wave divergence and convergence zones, and the shape of the coastline are decisive factors for the placement of amber deposits, so it is reasonable to analyse the directional sedimentary structures and the reconstruction of paleocurrents as important factors affecting amber deposition in the coastal zone.

Observations related to the experimental model of amber deposition in the coastal zone show a close substantive connection with the hypothesis that amber deposits should be associated not with areas of deltaic hollows, but with the extreme distal parts of the delta, the sediments of which were subsequently processed by wave action and became part of the barrier facies. The authors of the article emphasise that these regularities should be taken into account when setting up prospecting and appraisal works for amber. These ideas were further developed by Czuryłowicz [4]. The resource potential of the "Gurka Liubartovska"(Poland, Lublin region) deposit was illustrated by a map describing the probability that the percentage of amber will reach a value higher than the established threshold. Taking into account that the best way to exploit the deposit is through open pit mining, the analysis included layers describing the thickness of the overburden and a series of deposits developed at the stage of building the stratigraphic model. In papers by Nieć et al. [5, 6], models of amber deposits are presented and, on this basis, the choice of a method for their exploitation is proposed, taking into account mining and geological conditions.

Ukraine also has experience in developing models of amber deposits. Lustyuk, Dyakon and Rachkovsky [7] employs the method of continuous kriging, which means that the mass of each sample is assigned to the content of each sample, which ensures the minimum variance of the average content estimate. The mass of samples is determined by geostatistical methods, taking into account the geometric shapes, sizes and relative positioning of the samples of the block being evaluated. In general, the more distant the sample is from the centre of the block, the lower the weight assigned to it. The estimation of reserves by this method was based on the commercial implementation of the complex of mechanical and hydraulic testing of the Klesiv amber deposit in Rivne region.

The considered mathematical model allows to obtain an estimate of the average content in the blocks explored by the systems of excavation chambers, passed by the method of mechanohydraulic extraction. The considered mathematical model allows to obtain an estimate of the average content in blocks explored by systems of excavation chambers, passed by the method of mechanohydraulic extraction of large diameter wells (exploration wells), and also refines the estimates of average block content of useful components. This methodology allows to exclude systematic errors in the estimation of average grades in rich blocks, which are closely related to the problem of hurricane samples, which often arises in the exploration of amber deposits in Ukraine. The authors of the article present a flowchart of amber reserves estimation using the proposed method. This scheme allows establishing the upper and lower boundaries of the "sands" layer, as well as determining the volume of "peat" to be excavated and the volume of "sands" to be processed.

That is, an important aspect of model building is the representation of the space within which the parameters of the geological environment are studied. It should also be noted that spatial dependencies play a significant role in the construction of field models. Currently, a researcher has many possibilities for representing space. On the one hand, it is necessary to determine the dimensionality of the space (one-, two- or three-dimensional space), and on the other hand, to resolve the issue of representing the space in a continuous or discrete form. In the latter case, it can be a series of columns representing a certain topographic element.

Surfaces can also be described in an approximate discrete form using a series of prismatic rectangular sections of different heights. The heights of the prisms form a sequence of numbers, each of which is characterised by two coordinate values corresponding to a geographical location. Various options for the grid basis are given in [8]. The practical implementation of the space representation in a discrete form is the construction of block models, where blocks with different levels of mineral content are shown in the volume of the geological body. They are based on mathematical models and 3D modelling algorithms developed by various research centres: American, French, Norwegian, etc. There are many commercial software programs for this purpose, many of which have been used in petroleum geology [9]. An example of such modelling for nickel laterite deposits is given in [10]. Such models, in their computer implementation, make it possible to identify the most investment-attractive areas of deposits – areas of priority development. Mining parameters and geological and economic indicators are added to geological indicators.

Similar approaches have been used in Ukraine for ilmenite and other heavy minerals [11–13], as well as amber [14, 15]. However, the identification of investment-attractive sites requires the use and analysis of a set of geological and economic indicators. This approach was best developed on the example of the Torchynske ilmenite deposit, where an integral indicator was calculated to identify blocks with optimal economic and geological parameters, which is calculated as the difference between the notional value of the ilmenite concentrate and the cost of stripping and processing of the productive formation [12]. Such models have not been developed sufficiently for amber deposits.

In this article, we provide a method for the rapid assessment of geological and economic indicators of amber deposits (content and value of amber, costs of overburden excavation and extraction of "ore" with its subsequent processing, etc.) using integrated approaches to create technical and economic parameters of the deposit, in this case, using the ArcGIS geographic information system. Geological data helps determine the location of minerals and other geological aspects, while technical and economic parameters determine the efficiency of resource extraction. This interaction of geological data and technical and economic parameters of the deposit provides the necessary information to form a complete understanding of the subsoil potential, providing a basis for developing strategic management decisions.

The capabilities of ArcGIS geographic information system tools for geological research are virtually unlimited. With the acquisition of experience and an increase in the level of expertise, the functionality of the software environment and the possibilities of creating a working database are expanded. Understanding the principles of operation of various tools allows their effective combination to achieve new opportunities for data processing and interpretation.

The most important geological characteristics of any mineral deposit are a consequence of the process during the formation. Therefore, high-quality genetic modelling is the best basis for a complete geological definition of a mineral deposit, and with it safer conditions for the development of the deposit and greater profit in the overall complex. Many of the elements obtained through genetic modelling are directly applicable in the relevant submodels of geological and economic models. This is especially true for the metallogenic and geological submodels, and partially for the mining and technological, geo-environmental, and other submodels. The combination of genetic studies of conditions and pathways of formation is the basis on which the superstructure is given through the adjustment of some segments in the geological and economic model, especially for the technical and economy elements [16].

The object of modelling is the Zalissia amber deposit located in Sarny district of Rivne region (figure 1). In geostructural terms, the site is located within the northern part of the Volyn-Podolsk plate. According to the mineralogical zoning, it is located in the Dubrovytsia amber-bearing district of the Volodymyrets-Dubrovytsia amber-bearing zone of the western part of the Prypiat amber basin.

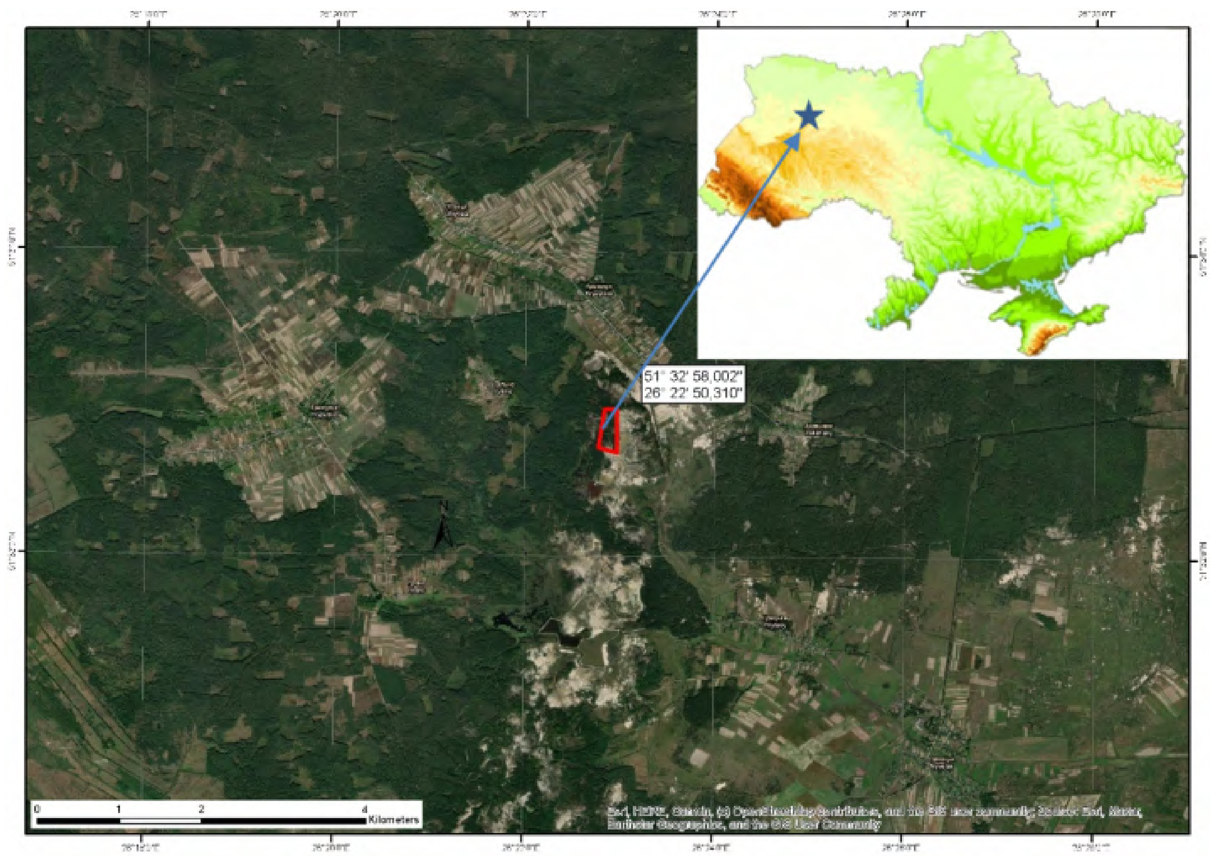


Figure 1. Location map of the Zalishke amber deposit, Sarny district, Rivne region.

According to the results of a detailed geological and economic evaluation, the site contained sediments of the Paleogene, Neogene and Quaternary systems in the borehole sections. The Paleogene system within the area is represented by the Obukhiv formation of the Eocene and Mezhyhirska formation of the Oligocene.

The amber-bearing sediments at the site are those of the Mezhyhirska Formation, which overlie the sands and siltstones of the Obukhiv Formation. The strata are represented by quartz sands, fine-medium grained with gravelly quartz grains and flakes of dark-coloured minerals. The sands are of medium to good coarseness, with rare grains of glauconite and small fragments of lignified wood. There are also occurrences of pyrite, pebbles of flints and quartz and crystalline rocks. In addition to sand and gravel deposits, the Mezhyhirska Formation is represented by nests of multi-coloured clays, dark grey-green, with mica flakes, inclusions and layers of lignified wood and some pieces of amber. Sedimentation of the Mezhyhirya Formation occurred in lagoonal-deltaic conditions.

2. Methodology

In this study, the method of modelling in a geographic information system using the ArcGIS computer program was applied. This programme is a system that allows collecting, organising, managing and analysing spatial information. The feature of using this method is the ability to work with vector and raster data that have a spatial reference to perform mathematical, statistical and spatial operations with data and to present them in the form of graphical depictions or data arrays.

During mining operations, technical and economic parameters are not stable (such as overburden excavation cost, processing cost, cost of raw materials) and even changes in the cost of fuel and lubricants can significantly affect the profitability of a deposit. This model allows us to make strategic decisions on the most efficient, productive, and rational development of a deposit.

The initial materials for the work were the data of exploration drilling of the Zalissia amber deposit, which underwent a detailed geological and economic evaluation. To build the model, the following parameters were set: boreholes (with geological parameters specified in the attribute plate: overburden thickness, productive rocks and amber content), corner points and the outline of the special permit boundaries.

3. Modelling process and results

The modelling study consisted of the following stages:

The first stage is the extrapolation of the edge boreholes beyond the boundaries of the special permit. This is done to ensure that the model fully covers the area of the site during interpolation.

The second stage is interpolation of the values of overburden thickness, productive rocks and amber content in the rock within the special permit. For this purpose, the Topo to Raster tool is used to create hydrologically correct models that are closer to the natural geological situation [17]. To interpolate the amber content, the Kriging tool was used (figure 2).

The key role in this model is played by the raster cell size. This parameter is crucial for this model because the raster cell size determines the area of the segment. Depending on the size of the field and the width of the working area, the cell size may vary. For example, in this model, the cell size is 20 m, so the cell area is 20x20=400 m^2.

The third stage is the display of economic data based on geological information using the Raster Calculator tool. During the geological and economic assessment of any stage, the following indicators are set for the deposit: the cost of removing 1 m^3 of overburden and processing 1 m^3 of amber-bearing ore. The following values for these indicators will be used for the model: the cost of overburden excavation – 25 UAH/m^3, the cost of amber-bearing rocks processing – 100 UAH/m^3.

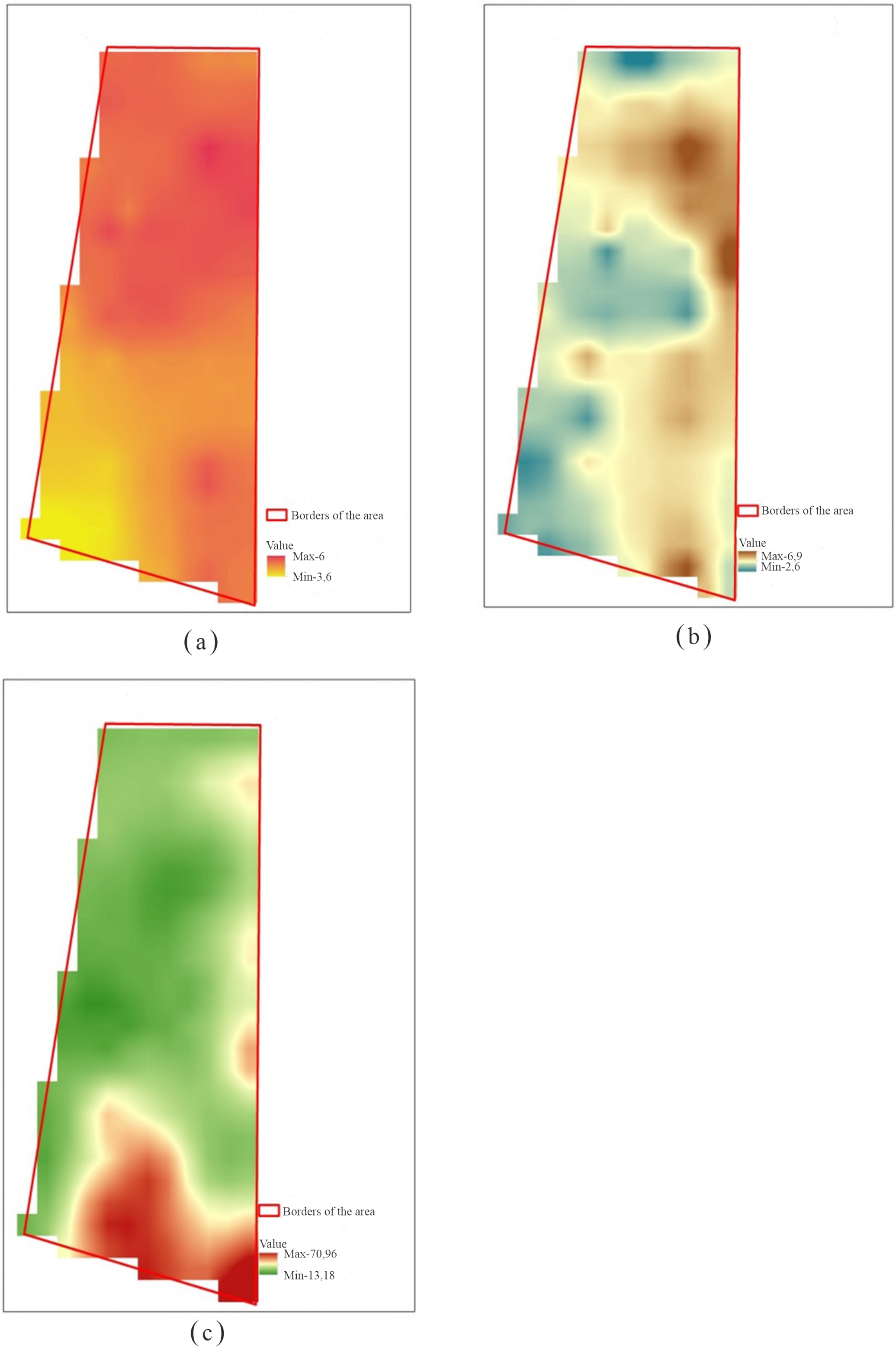


Figure 2. Interpolation of deposit parameters, (a) the thickness of the stripping rocks, (b) the thickness of productive rocks, (c) amber concentration.

In the Map algebra expression window, the following formulas were entered:

- For overburden – “Overburden thickness” (raster obtained by interpolation) x 25 (cost per unit of overburden excavation) x 400 (raster cell area)
- For ore deposit – “Ore deposit thickness” x 100 (cost per unit of ore processing) x 400 (raster cell area)
- To calculate the amount of amber in the subsoil -(“Ore deposit thickness” x “Amber content” x 400 (raster cell area)) / 1000 (to convert grams to kilograms)

For calculation the value of amber in the subsoil – (“Amount of amber in the subsoil” x 10735 (UAH, amber value) [18]. To display values in segments, the raster must be converted to points using the Raster to Point tool [19], which will create a point with raster attributes in the centre of each cell. The resulting maps are shown in figure 3.

The fourth step is to use the Raster Calculator tool to calculate the profitability of each segment based on the previous rasters. In the Map algebra expression window, we use the following formula: - “Cost of amber in the segment” – “Cost of overburden excavation” – “Cost of amber-bearing ore processing”. The resulting raster is a graphical representation of the financial results of the development of the deposit segments (figure 4).

Additionally, you can select the cells that will generate higher than average income, for example, for this model this value is 350453 UAH. The first year of operation of a mining company requires more capital investment, and therefore it is advisable to start development in those parts of the deposit that will bring the most profit at the initial stage. To identify such parts of the field, we will select all segments that are greater than or equal to the average. To do this, use the Create Fishnet tool to create a polygon network similar to the size of the raster cell and compare it with the raster. Select the necessary cell points using the Select by attributes tool and copy the selected points. Using the Select by location tool, select the polygons that correspond to the points and select them in the Switch selection attribute table, create a new column with an arbitrary name and assign a value of 1 to all selected polygons using the Field Calculator and display these polygons with a solid fill in the Display tab. The field segments highlighted in this way represent those areas that will generate above-average revenues and serve as a marker for identifying areas for priority commercial development.

The model is flexible, and when operating costs change, such as fuel prices or obtaining additional exploration data, the model is quickly recalculated to take into account such changes and their impact on future mining operations. Additionally, royalties, deforestation, stumpage, reclamation, etc. can be taken into account.

When modelling other deposits, segments with negative profitability may appear, which will serve as a warning to the subsoil user that it is unreasonable to develop part of the deposit or that it is necessary to change equipment or production methods.

4. Conclusions

The presented research and the developed method can be the basis for the development of an integrated geological and economic digital model and information and analytical support that can be used at all stages of research and development work on the study of amber content, resource development and objective assessment of mineral deposits, which is determined by the need to invest in further development. The main task is to determine whether the expected revenues from the operation of the deposit will be large enough to compensate for the costs and provide investors with an adequate level of profitability. Successful field development also has a significant impact on the overall economic and social development of the region and the country. The development of a new methodology for defining a mineral deposit is critical to attracting investment and developing regions, especially in depressed areas such as Polissya.

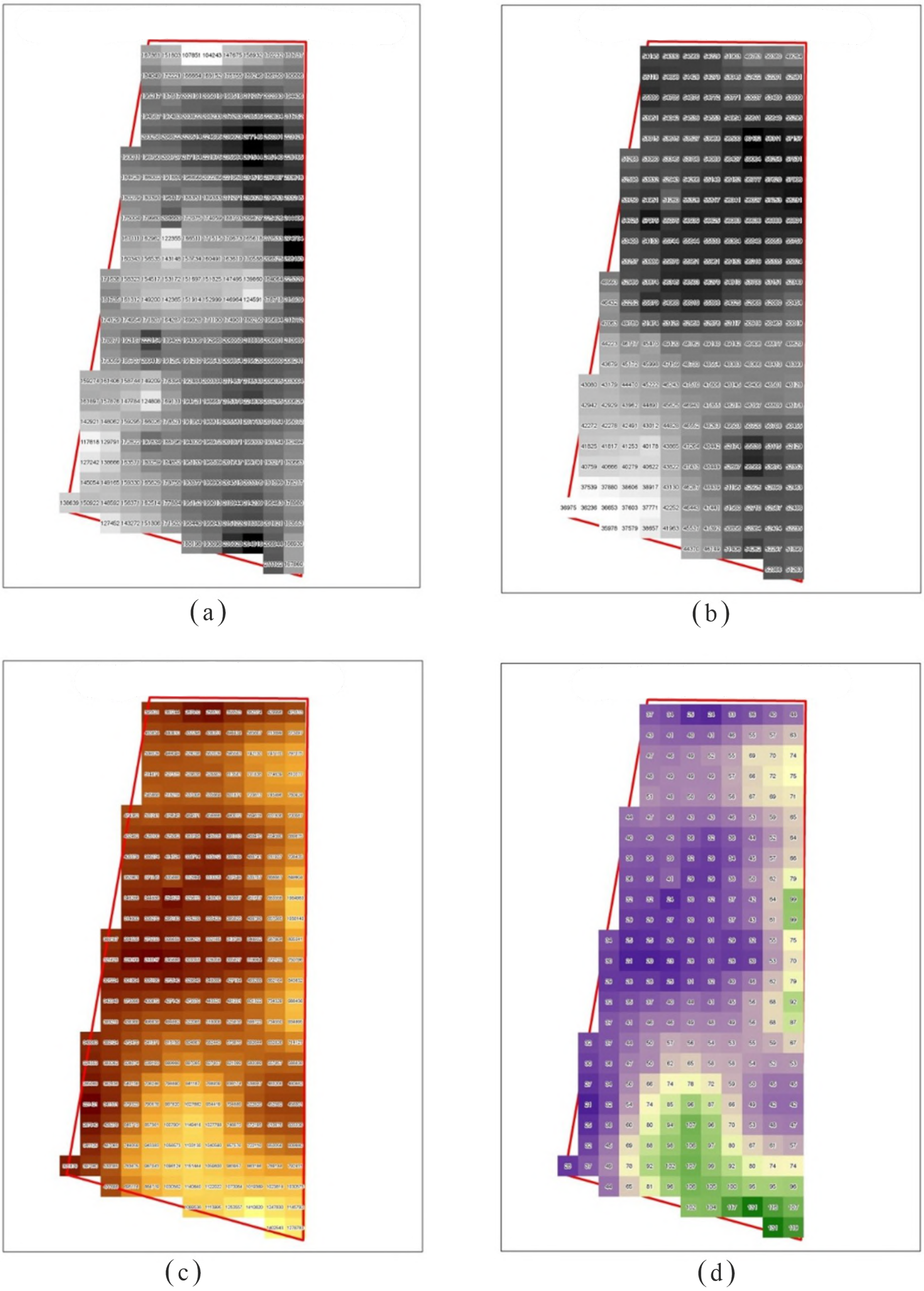
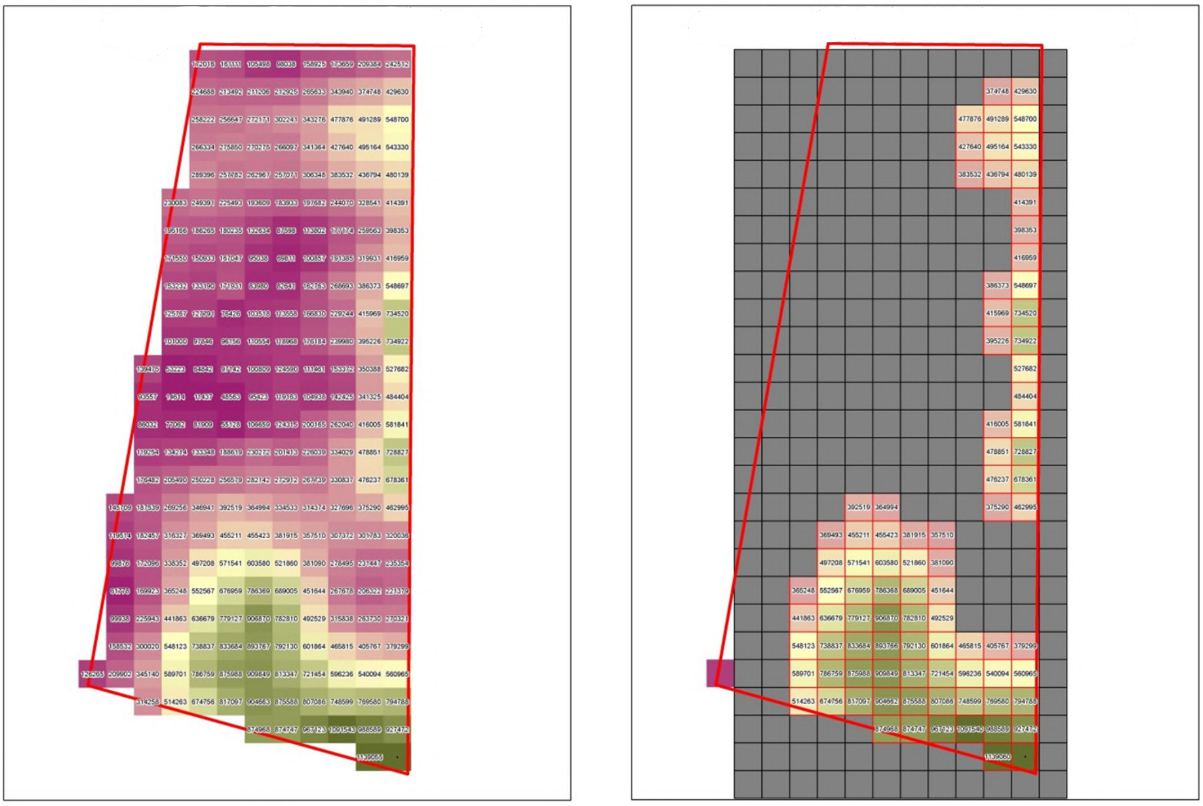


Figure 3. The resulting maps created using the Raster Calculator tool, (a) – costs of amber-bearing rock processing, (b) – costs of stripping operations, (c) – the cost of amber in the segment, (d) – amber weight in the segment (kg).



(a) (b)

Figure 4. Two-dimensional models of technical and economic indicators of field development, (a) – projected profit from the segment, (b) – segments with above-average profitability.

The study uses segment modeling – small (400 m^2) areas of one large deposit (for example, the area of the Zalissya deposit is 98,000 m^2), taking into account various attributes such as the cost of stripping, the cost of beneficiation, and the cost and quantity of raw materials in the subsoil. Based on these parameters, it is possible to predict the profitability/loss of each segment and determine the sequence of site development, risks and financial component of industrial development. The authors have highlighted the cells with segments with income that exceeds the average (for the Zalissia field, it is UAH 350,453). The selected segments with the highest income determine the areas of priority field development, which helps to maximize profits at the initial stage of development.

For a more efficient study of new deposits and assessment of their economic potential, the authors propose to use the tools of the ArcGIS program. This allows comparing the expected revenues from production with the corresponding expected costs of further exploration, development and production, objectively determining the suitability of the field for investment. ArcGIS provides the ability to store, process and analyze graphical and attribute data, which allows for a comprehensive assessment of the economic potential of a field. ArcGIS provides a comprehensive analysis of graphical and attribute data, helping to make management decisions.

The model of using simple mathematical methods in the design and geological and economic evaluation of an amber deposit emphasizes the accessibility and efficiency of the approach. The authors point out that such a model can be applied to other mineral deposits with simple mining conditions. This approach can be important for the sustainable economic and social development of regions and the country as a whole.

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Risks of the soil foundations stability losses of the Kyiv-Pechersk Lavra Dormition Cathedral due to the urban activities

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Risks of the soil foundations stability losses of the Kyiv-Pechersk Lavra Dormition Cathedral due to the urban activities

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Abstract. In the research, the use of numerical analysis of the soil foundations stability losses of Dormition Cathedral, where in the interiors of the II tier northern part, deformations of structural elements have been recorded since 2016, probably caused by uneven settlement of the foundations due to overmoistening. The initial data were the results of constant monitoring of the technical condition of the building, engineering and geological investigations, etc. To determine (confirm) the deformation factors and forecast their activation stabilization, a numerical calculation of the stress-deformation state of the cathedral soil foundations was performed for soils in their natural state and water-saturated state. The calculations of the stress-strain state of the cathedral foundations and the determination of plastic deformation zones were done using the PLAXIS software complex. They showed an increase in deformations in its northeastern part, under the basement premises, in particular for the scenario of flooding of the underground part. According to calculations, the plastic deformations of the base soil and, as a result, the deformations of structural elements are still in the stage of incomplete stabilization in the northern part of the cathedral, in the area where the basement part is located. The deformations extend the entire pile field under the construction of the cathedral, but do not reach the extreme minimum values in 8 cm. The main factor in the activation of deformations is the overmoistening of the soil massif, the impact of blast waves is not excluded (confirmation of which requires vibration monitoring). The direction of improving protection management measures for Dormition Cathedral is proposed.

1. Introduction

The territory of the Kyiv Pechersk Lavra National Reserve, the architectural ensemble of which is included in the UNESCO World Heritage List (no. 527), occupies a significant area and covers various geomorphological elements of the Dnieper slopes in Kyiv. Taking into account the complexity of the relief and the engineering-geological structure of the territory (the presence of soils with different physical and mechanical properties at the base of the monuments, erosional dissection of the relief, high groundwater levels, etc.), hazardous geological processes have become widespread, significantly affecting the technical condition and preservation architecture [1, 2].

The stability and preservation of the Lavra's objects are ensured by a system of special retaining and water-regulating engineering protection structures, controlled by constant monitoring, operating since 2009. However, in the context of growing urbanization impacts – building development within protected zones, accidents on water-carrying mains, etc., in recent decades the development of deformation processes is recorded on the monuments of the Reserve.

One of the attractions of the ensemble of the Reserve is the Dormition Cathedral – a unique building of ancient Russian architecture, partially preserved in authentic condition, and rebuilt in the forms of the 18th century [3–5]. The building was undermined in 1942. The restoration of the Cathedral began after 1996, when a decree on priority measures to revive St. Michael's Golden-Domed and Dormition Cathedral was signed. In 1981, a program for the revival of the Dormition Cathedral was approved. The project was developed by the UkrNIIproektrestavratsiya Institute [6]. The authentic strip foundations were strengthened with micropiles. Interior finishing work has not yet been completed.

Today, in the interiors of the northern part of the second tier of the Cathedral, horizontal cracks are recorded on the walls along the perimeter, at a height of about 2 m (the installed beacons are intact); vertical structural cracks of spalling of the brick mass of pilaster masonry from the plane of the load-bearing wall, with an opening of up to 1.5 cm (control gypsum beacons have been replaced since 2016 every 1-1.5 years) (figure 1); structural cracks around the spring-loaded arch and under the vault with an opening of up to 0.5 cm at the junction of the northern aisle with the main volume of the cathedral.

On the walls of the basement there are numerous traces of old wetting as a result of repeated flooding (destruction of the paint and plaster layers, formation of efflorescence); remains of suffusion soil removal on the floor (figure 2).

The deterioration of the technical condition of the building is probably caused by uneven settlement of the foundations due to waterlogging due to repeated basement flooding. One of

Figure 1. Structural cracks in the spalling of pilasters from the supporting (bearing) pillar, northwestern part of the 2nd tier (Preobrazhensky chapel).

Figure 2. Traces of flooding and soaking in the basements (red line – flood level).

these floods occurred on February 8, 2014. Near the northern apse of the eastern facade of the Dormition Cathedral, a fire hydrant was torn off in the inspection well, and flooding of the basement was recorded with suffosion removal of soil [7]. The waterlogging of the northern wall of the basement was probably caused by emergency leaks from the water supply in October 2021 (a rise in groundwater levels was recorded in GSS-101) and August 2022 (inspection wells were flooded throughout the Cathedral Square).

Flooding of the basements occurred repeatedly as a result of surface runoff entering the cathedral due to an imperfect drainage system from the adjacent territory, in particular due to abnormal rainfall. Further infiltration of water into the soil mass led to waterlogging of the loess soil layer, its subsidence and, as a consequence, to uneven settlement of the foundations. Also, the compaction of the loess soils at the base was caused by an increase in groundwater levels as a result of emergency leaks from networks (2016, 2017, the rise in groundwater levels was about 1 m). The rupture of plaster control beacons and stickers confirms this assumption.

With the beginning of full-scale hostilities as a result of the armed aggression of the Russian Federation, new technogenic influences of a military nature appeared on the reserve's monuments – the spread of blast waves when air targets were fired or hit by missiles, which could manifest itself in the deterioration of their technical condition, conditions of preservation and operation.

Monitoring of architectural elements in the interior of the cathedral indicates a deterioration in the technical condition of the monument in its northern part. The formation of horizontal cracks and spalling of pilasters probably entails uneven settlement of foundation piles; different pile depths; the piles are based on soils with different physical and mechanical properties; the unfinished process of initial subsidence of foundation soils should continue according to the project – 20-30 years after restoration [6].

Deformations that occur in the structural elements of monuments as a result of the action of certain processes require additional detailed and comprehensive analysis and development of solutions (protection management) to eliminate impact factors, preservation taking, into account the uniqueness of objects. It should be noted that the uniqueness of the historical objects of the Lavra makes it impossible to apply standard (destructive) research methods and approaches to strengthening and restoration work to them.

The purpose of the work is to calculate the stress-strain state of the soil foundations of the Dormition Cathedral and determine zones of plastic deformation and strain growth to determine the factors of deformation of structural elements and predict their activation/stabilization shortly and develop optimal (effective) restoration measures.

2. Materials and methods

The scheme of engineering protection of the territory (scale 1:1000); the plan of the current state of the Reserve (scale 1:1000); data of engineering-geological surveys [3, 5–7], geodetic plan (scale 1:500); data of engineering and geological investigations, the results of constant monitoring of the technical condition of the building materials are used.

The authentic strip foundations of the Dormition Cathedral were strengthened with micropiles with a diameter of 15-20 cm, which were deepened by 16-17 m. The load from the cathedral is transferred to the clayey soils of the Novopetrovskaya suite and moraine deposits. The height of the temple reaches 51.7 m, the thickness of the walls is 120-170 cm [3, 5, 6].

The natural basis of the Assumption Cathedral, as well as other monuments on Cathedral Square, is a layer of Upper Quaternary eluvial and aeolian-deluvial undifferentiated sediments (Priluki, Uday, Vitovsky, Bug, Dofinovsky and Black Sea horizons). The geological structure [6] distinguishes 10 engineering geological elements (IGE). IGE-1 bulk soils with a thickness of 1.9-3.5 m lie on the surface. Further down the section:

- loess-like sandy loam IGE-2 with a thickness of 11-13 m;
- loess-like loam IGE-3 with a thickness of 2-3 m;
- sand layer with gravel IGE-4, thickness 1.5-2 m;
- fine quartz sand IGE-5;
- semi-solid loam (moraine) IGE-6;
- fine sand, medium density IGE-7;
- plastic sandy loam, with layers of sand IGE-8;
- hard, brown clay IGE-9.

The basis of the existing strip foundations of the Assumption Cathedral are loess-like sandy loams (IGE-2). The consistency of soils in their natural state is solid.

Compression tests using the one- and two-curve method show a slight tendency of soils to subsidence (relative subsidence ϵ_{sl} <0.01), which gave grounds to consider soils as non-subsidence when designing foundations [6].

Calculation of the stress-strain state of the soil foundations of the Dormition Cathedral and determination of zones of plastic deformation was carried out using a numerical method using

Table 1. Physical and mechanical properties of the Dormition Cathedral soils foundations.

No. IGE	Unit weight γ_{unsat}, kN/m^3	Unit weight γ_{sat}, kN/m^3	Young's modulus, kN/m^2	Poissons ratio	Cohesion, kN/m^2	Friction angle, °	Perme ability, m/day
IGE-1	17.1	19.7	15000	0.35	48.2	24	0.2
IGE-2	18.4	19.4	18000	0.4	24	17	0.5
IGE-3	26.8	26.8	19000	0.4	29	24	0.5
IGE-4	16.8	18.6	13000	0.35	18	22	0.05
IGE-5	18.2	19.4	12000	0.3	2	31	4
IGE-6	17	21	18000	0.3	60	25	0.05
IGE-7	16.8	17.8	30000	0.3	2	31	2
IGE-8	16.8	19.5	15000	0.35	22	18	0.05
IGE-9	19.4	20.2	20000	0.4	95	12	0.005

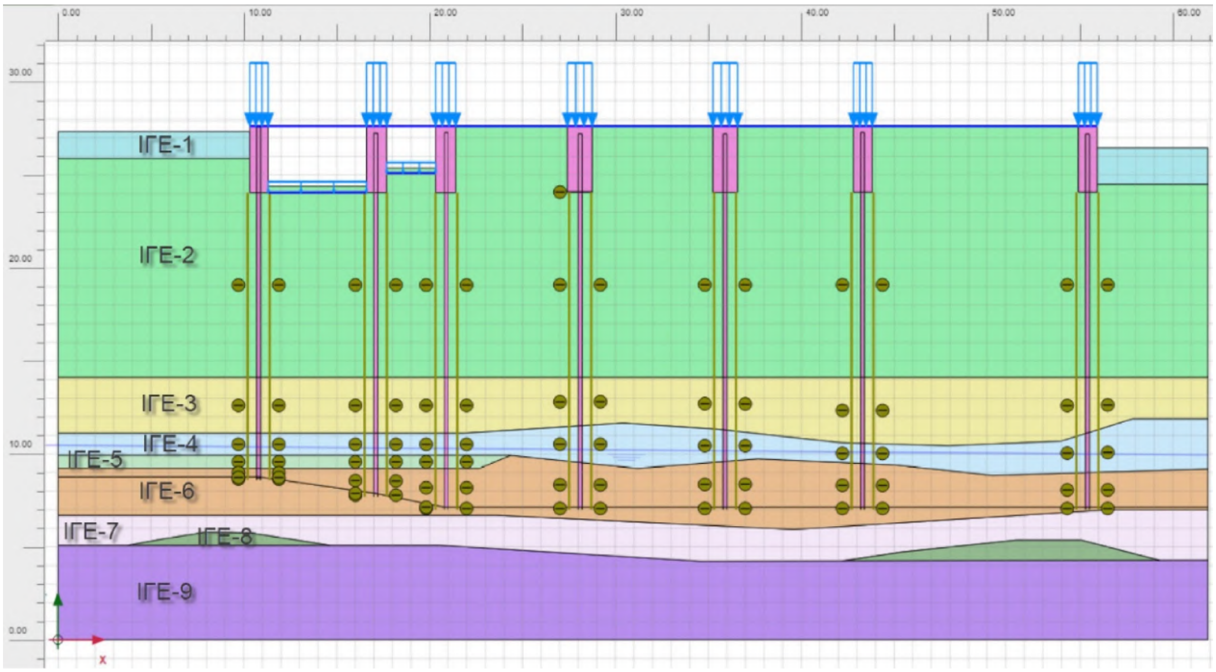


Figure 3. Calculation diagram of the Dormition Cathedral soil foundations.

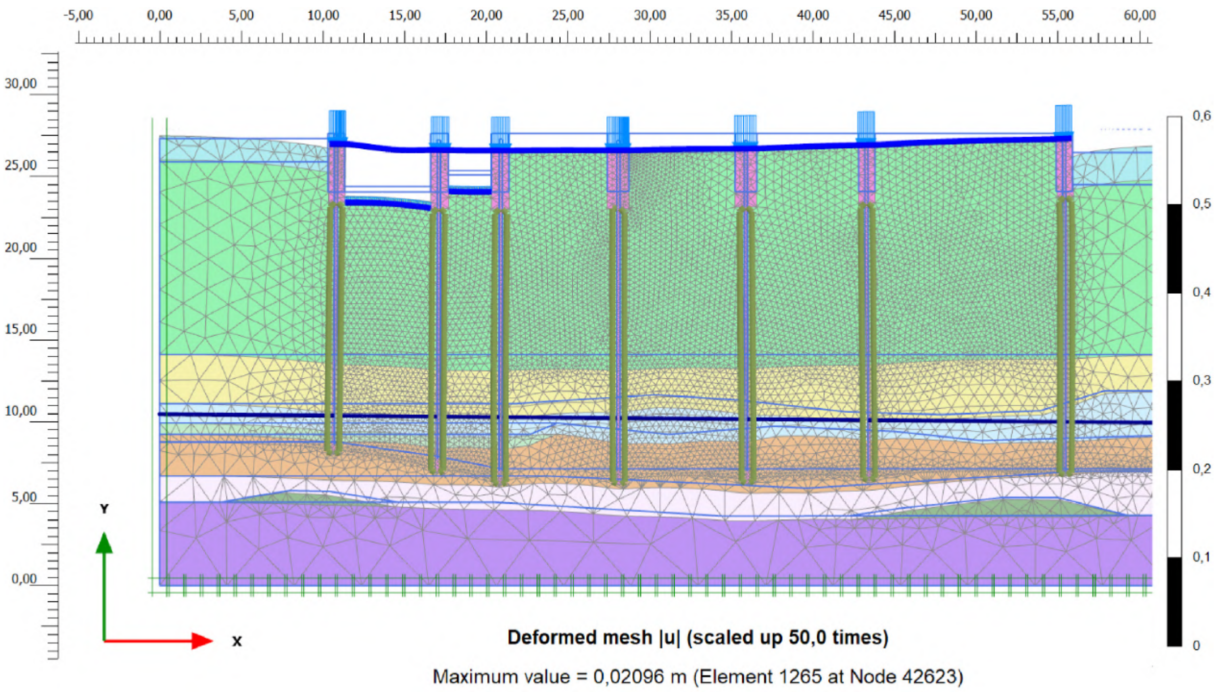
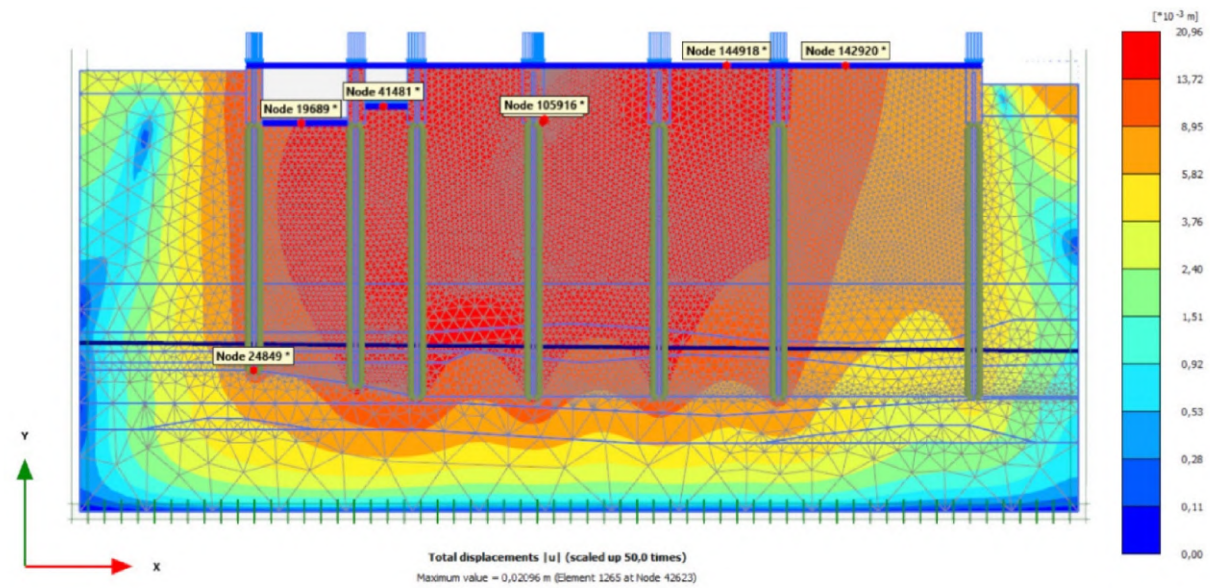


Figure 4. Scheme of the deformation grid of the soil massif after modelling.

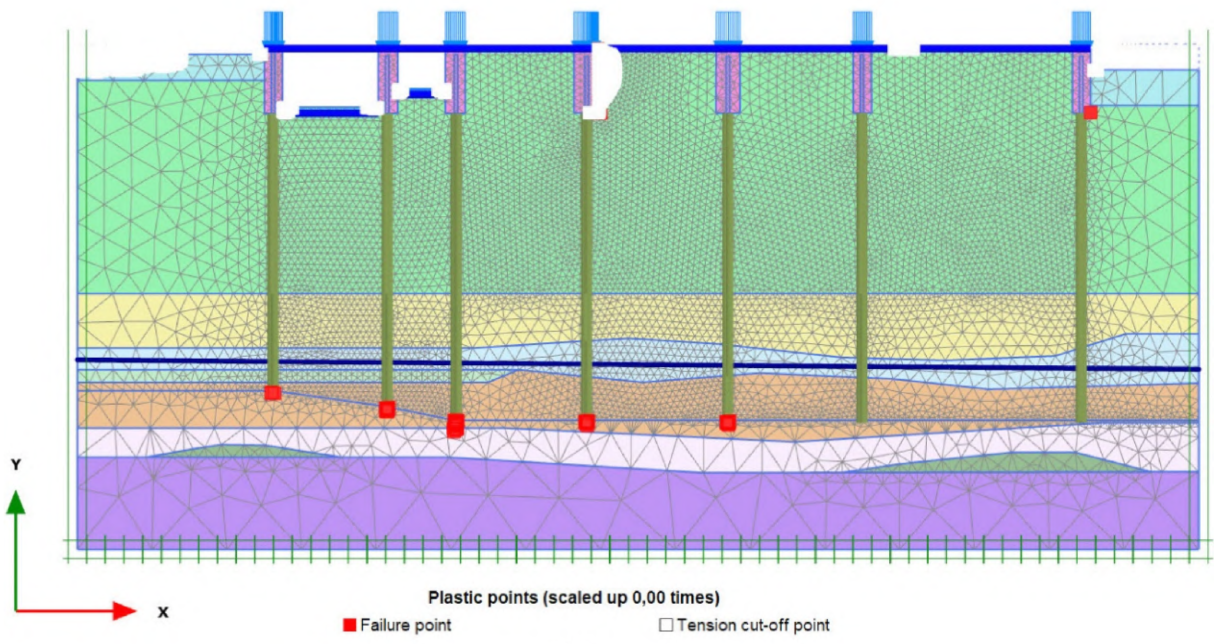
the finite element analysis package PLAXIS [8,9]. The physical and mechanical properties of the IGE isolated in the foundations of the cathedral are summarized in table 1. The Mohr-Coulomb model was applied for all IGEs.

The geological section diagram shown in figure 3 was used for the calculation. When constructing the model, slabs were used to specify the overlap of foundations, interfaces were used to model contact surfaces between piles and soils. The load on the foundations of the cathedral is specified by a distributed type of effort for slab and strip foundation types. The geometric model of soil clusters was imported in *.DXF format from a computer-aided design software environment, where it was created at an internal scale of 1:1000. The absolute elevation of the surface on the right corner of the model is 186.2 m, at the point (0.0; 0.0) – 159.8 m. Pore pressure and external water pressure are generated based on the groundwater level – 172.4 m.

A plane problem was considered. Using the finite element method, the computational domain



a)



b)

Figure 5. General deformations (a), formation of plastic zones (b).

was discretized into 63,690 15-nodal triangular elements of small and medium size. The nonlinear deformation process is modeled stepwise according to the load parameter.

The calculation was carried out in stages reflecting the sequence of events from the natural state, construction, load from the weight of the cathedral and up to the emergency situation – flooding of the basement on the left side (figure 3). The conditions of each stage were set by activating/deactivating the corresponding model elements (soil clusters, engineering structures, loads).

3. Results

At the first stage, the soil mass is under the influence of loads from its own weight and from groundwater. The calculation type used is Gravity loading. The second stage took into account the construction of foundations, first strip foundations, then micropiles. At the same time, the stress state in the soil mass, calculated at the first stage, was taken into account, and the deformations were set to zero, which corresponded to the natural state of the massif at the time of construction. The type of calculation at this stage and subsequent ones is Plastic. As a result, the stress state in the massif was obtained from the own weight of the soil, groundwater and the load from engineering structures, and the deformations were determined from the load of the structures.

At the third stage, the load from the cathedral on the strip foundation elements was introduced into the calculation – 294 kN/m^2.

The fourth stage is modeling the flooding situation of the basement by specifying a band-distributed load on the foundation slab from the weight of the water column (50 kN/m^2).

The displacements of the finite elements of the design scheme are taken into account only after the fourth stage (figure 4).

In figure 5a, the diagram of total displacements is shown. The maximum values acquire a value of 0.02096 m after the fourth stage. The deformations cover the entire pile field under the cathedral building, but do not reach the maximum minimum values – 8 cm by [10–15]. The

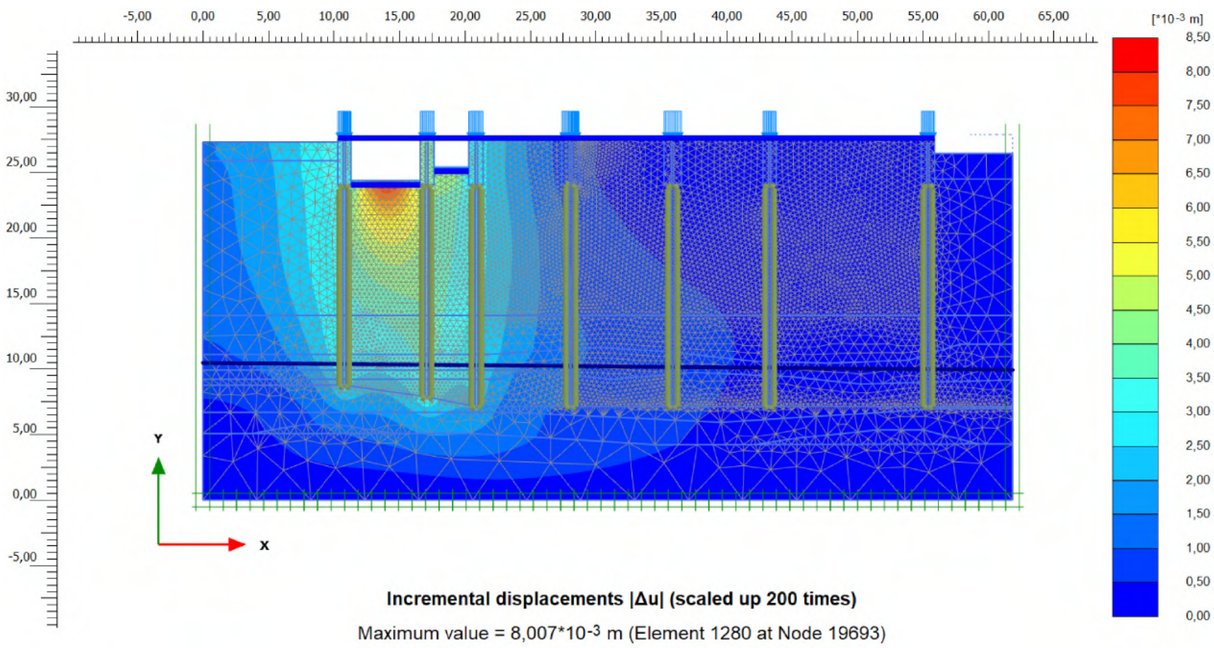


Figure 6. Increase in deformation after flooding of the cathedral basement part.

diagram of the formation of plastic zones in the massif is shown in figure 5b. Areas of possible displacements (red squares) are clearly visible. Clusters of white squares indicate plastic zones formed during tension.

Additional displacements are generated in a separate calculation step. General displacements have no physical significance, but additional displacements at the last stage (during flooding) provide an indication of the likely mechanism and locations of imbalance in the soil mass and, accordingly, places in the structural elements of the structure where cracks should be expected to appear.

Each stage of modeling shows an increase in deformations in the left part of the model under the basements of the cathedral, in particular after the flooding of the underground part, as shown in figure 6.

Curves in figure 7 shows all four simulation stages for control points. For each stage, the Mstage parameter varies from 0.0 to 1.0. A decrease in the slope of the curve in the last stage indicates an increase in the magnitude of plastic deformations. The calculation results show, however, that the soil mass remains stable at the end of the last stage.

The modeling carried out indicates that plastic deformations of the foundation soils are still in the stage of incomplete stabilization; the main risk of intensifying deformations at the present stage is waterlogging of the soil mass, both as a result of a natural rise in groundwater levels (overmoistening of soils at the base of the piles), and as a result of emergency leaks (waterlogging

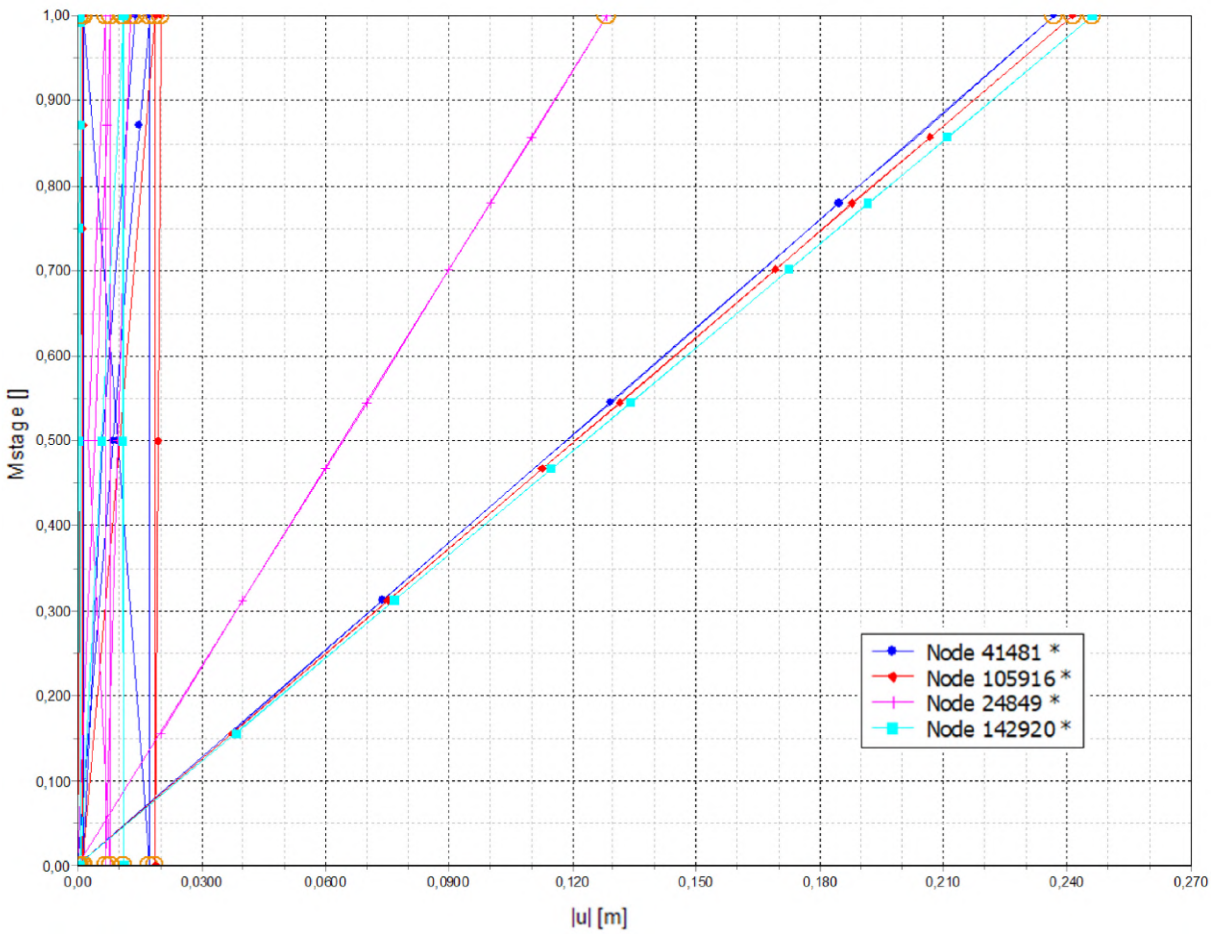


Figure 7. Load-displacement curve for observation points (Node).

of soils at the base of the cathedral's strip foundations).

4. Conclusions

Calculation of the stress-strain state of the soil foundations of the Dormition Cathedral and determination of zones of plastic deformation using the PLAXIS software package showed an increase in deformations in the northeastern part, under the basements, in particular for the scenario of flooding of the underground part. This is confirmed by field observations – it is in this place that deformations were recorded (vertical structural cracks of the brick mass of the pilaster masonry from the plane of the load-bearing wall, structural cracks around the spring arch and under the vault with an opening of up to 0.5 cm in the place of the cathedral).

Plastic deformations of foundation soils and, as a consequence, deformations of structural elements are still in the stage of incomplete stabilization; the main risk of intensification of deformations may be the processes of overmoistening of the soil mass, both as a result of a natural rise in groundwater levels and as a result of emergency leaks from networks, in incl. caused by damage to backbone networks as a result of military operations.

However, the calculation results show that at the end of the last stage, the soil mass remains stable and should provide the bearing capacity for the construction of the Cathedral. However, reliable operation and prevention of cracks and deformations in structural elements must be ensured by improving the management of protection measures according to research and norms [16–18].

Measures to minimize the impact of man-made leaks should be aimed at the following:

1. Reconstruction of water supply networks.
2. Current repairs with crack injection.
3. Modeling the stress-strain state of the structure.
4. Constant monitoring, incl. geophysical research.
5. Consolidation of loose soils.

Complex engineering and geological conditions caused by the presence of subsidence soils, excessive overmoistening of the soil base, which, among other things, causes the deterioration of the technical condition of unique structures, require the implementation of a comprehensive system of tools for instrumental "Structural Health Monitoring" (SHM) [19–21] of the objects of the Reserve into the existing monitoring system in the Reserve and the use methods of mathematical analysis of the received data streams. This will make it possible to track man-made, military (during missile attacks, UAVs) and other influences on structural changes in monument structures – the accumulation of microcracks, changes in the parameters of the spectral model of monument structures that cannot be reliably detected by visual surveys.

The preservation of the unique UNESCO World Heritage Sites of the Reserve requires further improvement of the comprehensive monitoring system (simultaneous observations of the microclimate of buildings, humidity of building materials, hazardous exogenous geological processes, etc.), using modern non-destructive monitoring methods and mathematical modeling. In particular, to determine the response to external influences, including those of a military nature, seismometric (vibrometric) equipment must be installed on the cathedral structures in its northern part. In order to determine (confirm the zones of soil decompression (plastic deformation) obtained by calculations (modeling), it is recommended to perform geophysical studies using electrical tomography).

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Features of mineral composition of garnet-bearing shales of the Kryvyi Rih basin and recommendations for further processing

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Features of mineral composition of garnet-bearing shales of the Kryvyi Rih basin and recommendations for further processing

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Abstract. In addition to iron ore, the deposits of the Kryvyi Rih basin contain about 50 types of metallic and non-metallic minerals, which are simultaneously extracted from the subsoil during the exploitation of the deposits and can be used in the national economy of Ukraine. An important place among them is occupied by garnets, which are rock-forming minerals of some types of granitoids, gneisses and crystalline shales. Garnet-bearing shales are widely distributed within the Kryvyi Rih basin. In this paper, we investigated garnet-bearing shales of the Hannivske field from the Northern region of the Kryvyi Rih basin. Based on the results of detailed studies, the mineral composition was established, their varieties were identified, and mineralogical recommendations for further processing technology were given.

1. Introduction

In addition to iron ore, the deposits of the Kryvyi Rih basin contain about 50 types of metallic and non-metallic minerals, which are simultaneously extracted from the subsoil during the exploitation of the deposits and can be used in the national economy of Ukraine [1]. An important place among them is occupied by garnets, which are rock-forming minerals of some types of granitoids, gneisses and crystalline shales [2, 3].

The Hannivske ferruginous quartzite deposit is located in the Northern Iron Ore District of the Kryvyi Rih Basin and is currently being developed by Northern Mining and Processing Plant, which uses poor magnetite ores as its raw material base. The deposit is located within the East-Hannivska metamorphic rock band, which is a northern extension of the Saksagansk iron ore band. The structure of the East Hannivska band includes rocks of all world Paleoproterozoic and Cenozoic series of Kryvyi Rih [4]. Syngenetic and epigenetic processes of ore formation led to the formation of the productive and host strata of the deposit, mineral and chemical composition of ores and rocks [5]. Dynamothermal metamorphism, sodium metasomatism, hydrothermal phenomena, and hypergenesis in the process of transformations of primary sediments caused the presence of poor magnetite ores and a number of associated minerals in the productive and host strata of the deposit: abrasive garnet, muscovite, facing and paving stones, amphiboles and pyroxenes as ceramic raw materials, mineral dyes, artistic pigments, manifestations of collectible and industrial raw materials: dispersed goethite, dispersed hematite jasper, crystals and aggregates of quartz, chalcedony, goethite and other minerals, etc. [4, 6]. Among the minerals of the deposit, a special place is occupied by garnet-bearing shales, which can be used to produce both high-quality garnet concentrate and high-quality collecting raw materials [7–9]. Garnet-bearing shales occupy a special place among the deposit's minerals. Garnet of the Hannivske deposit is a rock-forming mineral of the zero (40-80 m thick) and first (50-200 m thick) shale horizons. The formation of garnet is caused by dynamothermal metamorphism of primary alumina-iron-siliceous sediments in the epidote-amphibolite facies [4, 10]. The multi-stage formation of the Saksahanske and host strata of the Hannivske deposit, the diversity and activity of syngenetic and epigenetic geological processes have led to a variety of petrographic and mineralogical composition of the productive and host strata of the deposit. There are several mineral types of garnet-bearing shales. The most common within the deposit are garnet-quartz-biotite, cummingtonite-garnet-quartz-biotite, and garnet-biotite-quartz-cummingtonite. The average garnet content in shales varies from 5-7 to 20-25 vol.% [11].

Within the mining allotment of the Hannivske deposit, the resources of garnet-bearing shales amount to about 1 billion tonnes.

The purpose of this work was to conduct detailed mineralogical studies of garnet-bearing shales, identify their mineral varieties, and provide mineralogical justification for the possibility of producing garnet concentrate from garnet-bearing shales during further technological tests.

2. Methodology

In the framework of this work, the authors selected 25 initial samples of garnet-bearing shales in the faces of the Hannivske quarry, and 26 initial samples from the lithic collections of the Kryvyi Rih National University were added to the selected samples. The garnet-bearing shale samples are equally represented by the zero and first shale horizons of the Saksagan Formation of the deposit. Transparent and polished grinds were made from the material of all selected samples.

The authors carried out detailed geological and mineralogical studies of the garnet-bearing shales of the Hannivske deposit. All mineralogical studies were carried out using macroscopic and microscopic methods. Macroscopic studies were carried out visually and with the help of a binocular microscope, microscopic studies – using serial petrographic and mineralogical microscopes. Microhardness studies were carried out using a PMT-3 microhardness tester. From 30 to 34 garnet individuals were analysed in samples from certain types of shale of the Hannivske deposit – three micro-pressures in each. A load of 100 g was used. The total number of microhardness measurements was 507. The studies focused on the mineral composition of garnet-bearing schists, morphology and anatomy of garnet individuals, their fracture, and the nature of inclusions of ore and nonmetallic minerals. Geological, mineralogical, petrographic, and statistical methods of geological data processing were applied.

As a result of the studies, the existing knowledge about the localisation of garnet-bearing shales was clarified. The garnet-bearing shales of the Hannivske deposit were mineralogically characterised and their mineral varieties were identified. Mineralogical recommendations for their further processing were provided.

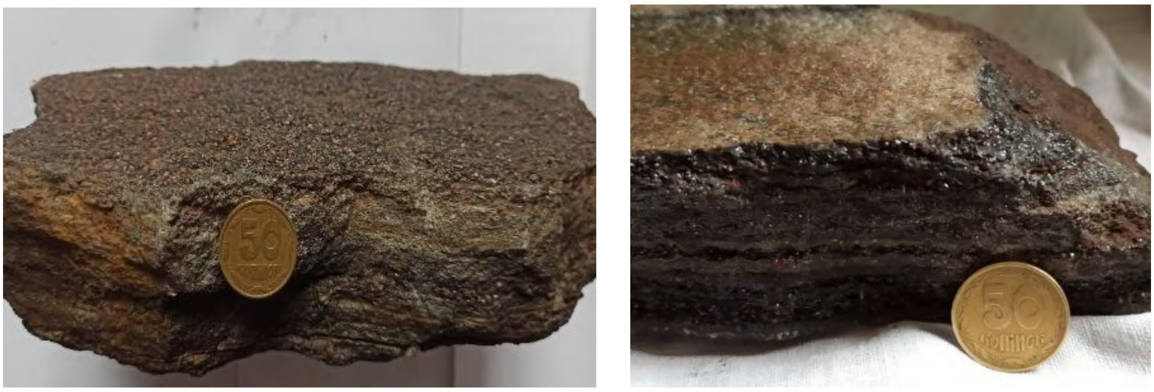
3. Results

Garnet-bearing shales are found in the shale horizons of the underlying strata of the Hannivske deposit, which are represented by the zero and first shale horizons. The basal position is occupied by the zero shale horizon. It, as well as the first shale horizon located above the section, is characterised by the most perfect mineralogical zonation among all shale horizons of the field. Its character is determined by the ratio of alumina content (increasing from the periphery of the horizon to its central part) and iron oxides (decreasing in the same direction) [5]. Thus, it can be concluded that the central zones of both (zero and first) shale horizons are composed of high-alumina shale, the intermediate zones – alumina-iron shale, and the peripheral zones – low-alumina, high-iron shale.

Garnet of the Hannivske deposit is a rock-forming mineral of the zero and first shale horizons. The most common rocks in the deposit are garnet-quartz-biotite, cummingtonite-garnet-quartz-biotite, and biotite-garnet-quartz-cummingtonite. The average garnet content in the shales varies from 5-7 to 20-25 vol.%.

Detailed mineralogical studies of the composition, structure, texture, morphology and anatomy of garnet individuals, their fracturing, and the nature of inclusions of ore and nonore minerals in garnet-bearing schists were carried out by the authors.

The rock texture of garnet-bearing schists is schistose, schistose-laminated, layered, and disseminated. The most common textures for garnet-bearing shales are shale and shale-laminated (figure 1).



(*a*) (*b*)

Figure 1. The most common textures of the original samples of garnet-bearing shales of the Hannivske field: (*a*) shale (*b*) shale-laminated texture.

Rock structure: granulopodoblast, porphyroblast. Based on the results of detailed microscopic studies of the initial samples, their quantitative mineralogical calculations and taking into account the results of previous studies, the authors identified five mineral varieties of garnet-bearing shales of the Hannivske field:

- type 1 – staurolite-biotite-quartz-muscovite shales with garnet;
- type 2 – garnet-muscovite-quartz-biotite shales;
- type 3 – garnet-quartz-biotite shales;
- type 4 – cummingtonite-garnet-quartz-biotite shales;
- type 5 – garnet-quartz-biotite-cummingtonite.

The results of determining their average mineral composition are shown in (table 1).

The data shows that the highest garnet content is characteristic of mineral type 4 (cumingtonite-garnet-quartz-biotite shale), with a garnet content of 18.23 vol.% in rocks of this type. The lowest garnet content is observed in the composition of type 1 (staurolite-biotite-quartz-muscovite schist with garnet), the average garnet content in this type does not exceed 1.35 vol.%. For mineral type 5 (garnet-quartz-biotite-cummingtonite schist), the garnet content is also significantly increased and amounts to 12.26 vol.%. For mineral types 2 and 3 (garnet-muscovite-quartz-biotite schist and garnet-quartz-biotite schist), the average garnet content is 5.45 and 9.86 vol.%, respectively.

Table 1. Average mineral composition of mineral varieties of garnet-bearing shales of the Hannivske deposit.

Minerals and mineral varieties	Mineral varieties of garnet-containing shales				
	type 1	type 2	type 3	type 4	type 5
	Mineral content, vol.				
Cummingtonite	0.00	0.10	4.12	14.19	35.35
Muscovite	35.88	25.35	3.93	0.10	0.01
Garnet	1.35	5.45	9.86	18.23	12.26
Magnetite	0.07	0.40	0.60	1.00	3.01
Hematite	0.00	0.00	0.02	0.03	0.05
Iron hydroxides (goethite, hydrogelite)	0.01	0.03	0.03	0.09	0.18
carbonates (calcite, dolomite, etc.)	0.71	0.95	1.02	1.26	1.32
chlorite	0.32	0.45	1.00	0.65	0.68
staurolite	7.15	0.30	0.02	0.00	0.00
disten	0.81	0.10	0.02	0.02	0.00
andalusite	0.52	0.10	0.01	0.00	0.00
graphite	2.18	2.06	0.82	0.20	0.07
relict silicates (albite, oligoclase, magnesioribekite, etc.)	0.20	0.30	0.38	0.52	0.90
relict sulphides (pyrite, pyrrhotite, chalcopyrite, etc.)	0.32	0.31	0.32	0.3	0.29
apatite	0.17	0.16	0.16	0.17	0.20
other minerals (zircon, tourmaline, etc.)	0.29	0.35	0.30	0.29	0.28
Total	100.00	100.00	100.00	100.00	100.00

Note: mineral varieties type 1 – 9 samples; type 2 – 11 samples; type 3 – 12 samples; type 4 – 10 samples; type 5 – 9 samples.

Due to the fact that garnet-bearing shales of the Hannivske deposit are considered as a promising raw material for the production of garnet concentrate, the authors conducted mineralogical studies to investigate in detail the morphology and anatomy of garnet individuals, the nature of inclusions of ore and nonore minerals in their composition, and the fracture of garnet.

Crystallomorphological studies of garnets from the initial samples allowed the authors to identify two main habit forms of garnet crystals: tetragon-trioctahedron {211} and rhombododecahedron {110}. No other forms were found during mineralogical studies.

The habit forms for garnet crystals of different sizes were also determined. Figure 2 shows the frequency of occurrence of habitual forms of garnet individuals of the Hannivske deposit depending on their size.

According to the data obtained, it can be said that the process of crystal growth was accompanied by a gradual evolution of their shapes from rhombododecahedron to tetragon-trioctahedron. This can be explained by the accelerated growth of the rhombododecahedron faces and the associated gradual degeneration of the vertices.

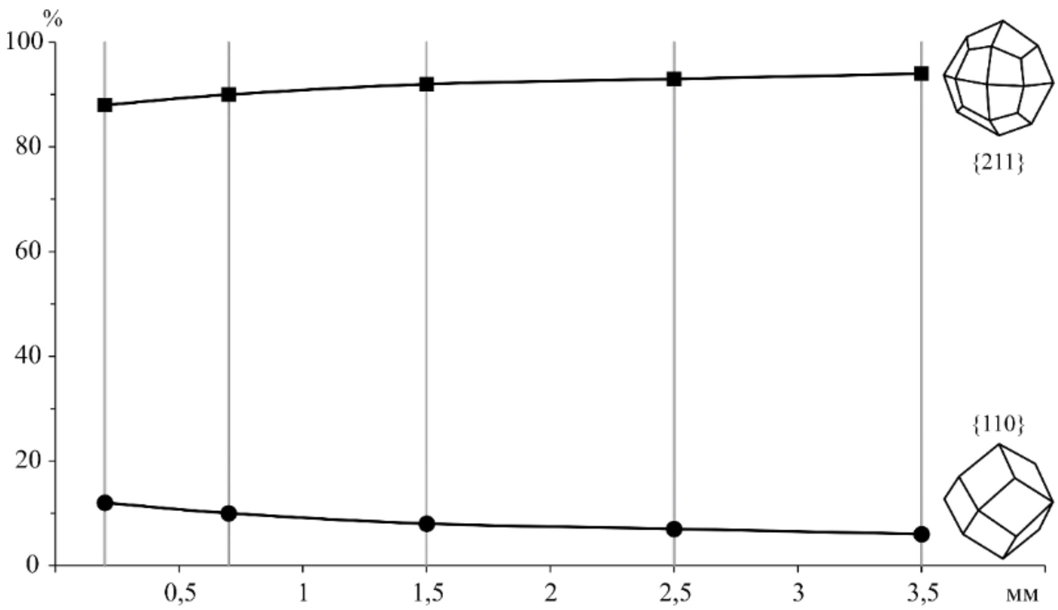


Figure 2. Occurrence of habitus forms of garnet crystals of the Hannivske deposit depending on their size.

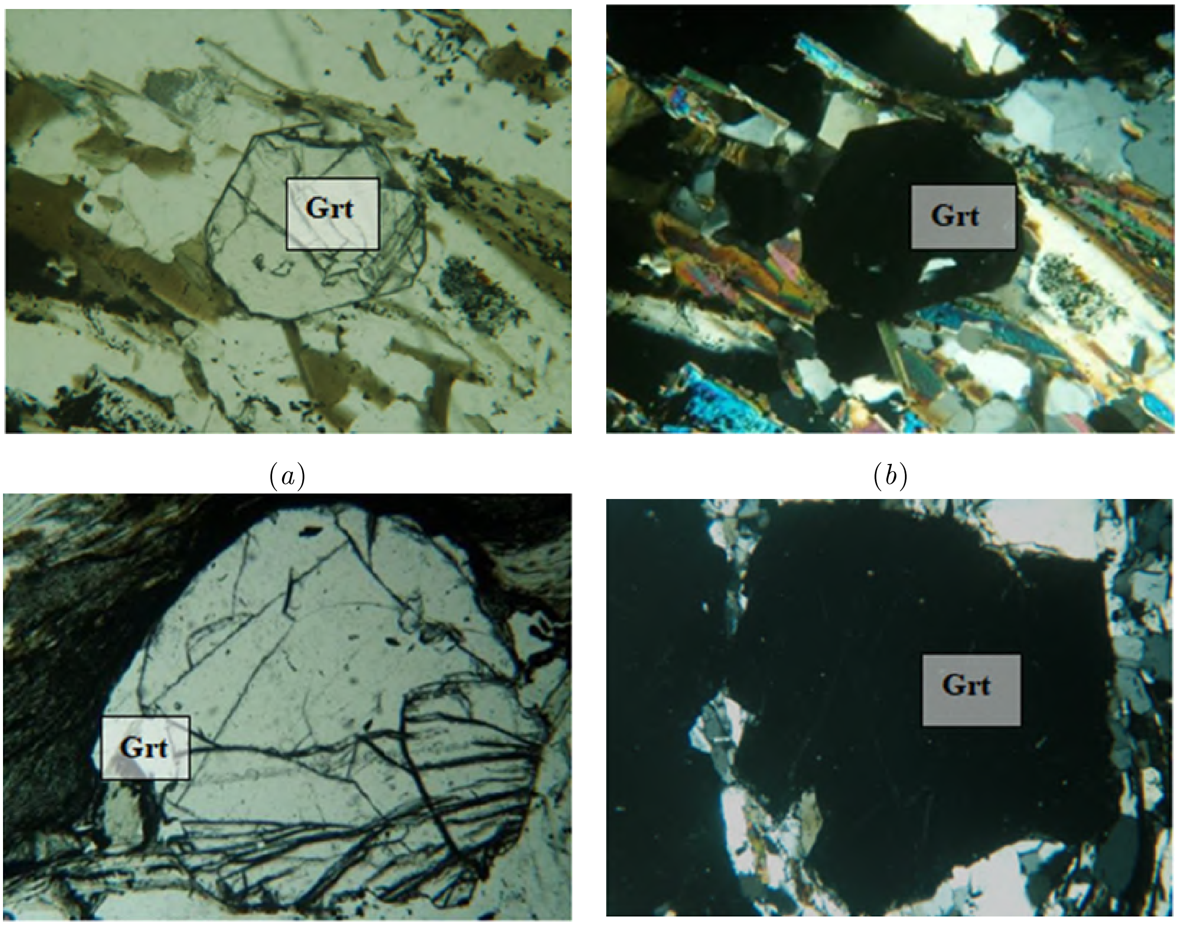
The combination of the rhombododecahedron and tetragon-trioctahedron shapes gives garnet crystals an isometric appearance that is close to spherical. During mineralogical observations, considerable attention was also paid to the correctness (idiomorphism) of the shape of garnet individuals. It was found that the shape of garnet grains in the studied initial samples is diverse. Most often, garnet crystals are found in the isometric form of hypidiomorphic (figure 3a, b), xenomorphic with rounded outlines (figure 3c) and xenomorphic with "torn" edges ((figure 3d).

Correct habitual forms are typical for garnet crystals whose size does not exceed 2.5-3.0 mm. With the increase in the size of crystals, distortion of their shapes is observed, as well as the appearance of complex fusions with individuals and aggregates of cummingtonite, biotite, and quartz. Thus, the increase in the size of garnet crystals is accompanied by a decrease in their perfection, which will significantly impair the enrichment of garnet-bearing shales.

The crystals of the main rock-forming minerals (cummingtonite, biotite, quartz) in the shale have completely opposite shapes – cummingtonite is characterised by a columnar appearance, muscovite and biotite by a lamellar appearance, quartz most often forms irregularly shaped xenomorphic formations in the main fabric of the shale.

Individuals of garnet from the Hanna deposit are characterised by a predominant crystal size of 1-2 to 5-10 (sometimes 15-20) mm. The authors have measured the average size of garnet individuals for all the identified mineral varieties of garnet-bearing shales. The measurements were made in transparent and polished grinds and cuts of the original samples using an eyepiece micrometer with a ruler. The average value of the determinations was taken as the mean value crystals in the rock of each mineral type. The results of the determinations are shown in (table 2).

It was found that the average size of garnet crystals naturally increases from staurolite-muscovite-quartz-biotite shales (mineral type 1), which occupy a central position in the shale horizon, with the average size of garnet individuals in shales of this type being 0.92 mm, to garnet-quartz-biotite-cummingtonite (mineral type 5), which are located in the peripheral parts of the shale horizons. The average size of garnet crystals in them is 3-4 times higher than the average size of garnet crystals from the central parts of shale horizons and reaches 3.68 mm. This is due to an increase in the activity of metamorphogenic mineral formation processes



(*a*) (*b*)

(*c*) (*d*)

Figure 3. Hypidiomorphic and xenomorphic garnet individuals in garnet-bearing shales of the Hanniske deposit: transmitted light; without the analyser (*a, c*) and with the analyser (*b, d*); 35x magnification. Grt – garnet.

Table 2. Distribution of garnet crystals (vol.%) by size class and their average size from garnet-bearing shales of the Hannivske deposit.

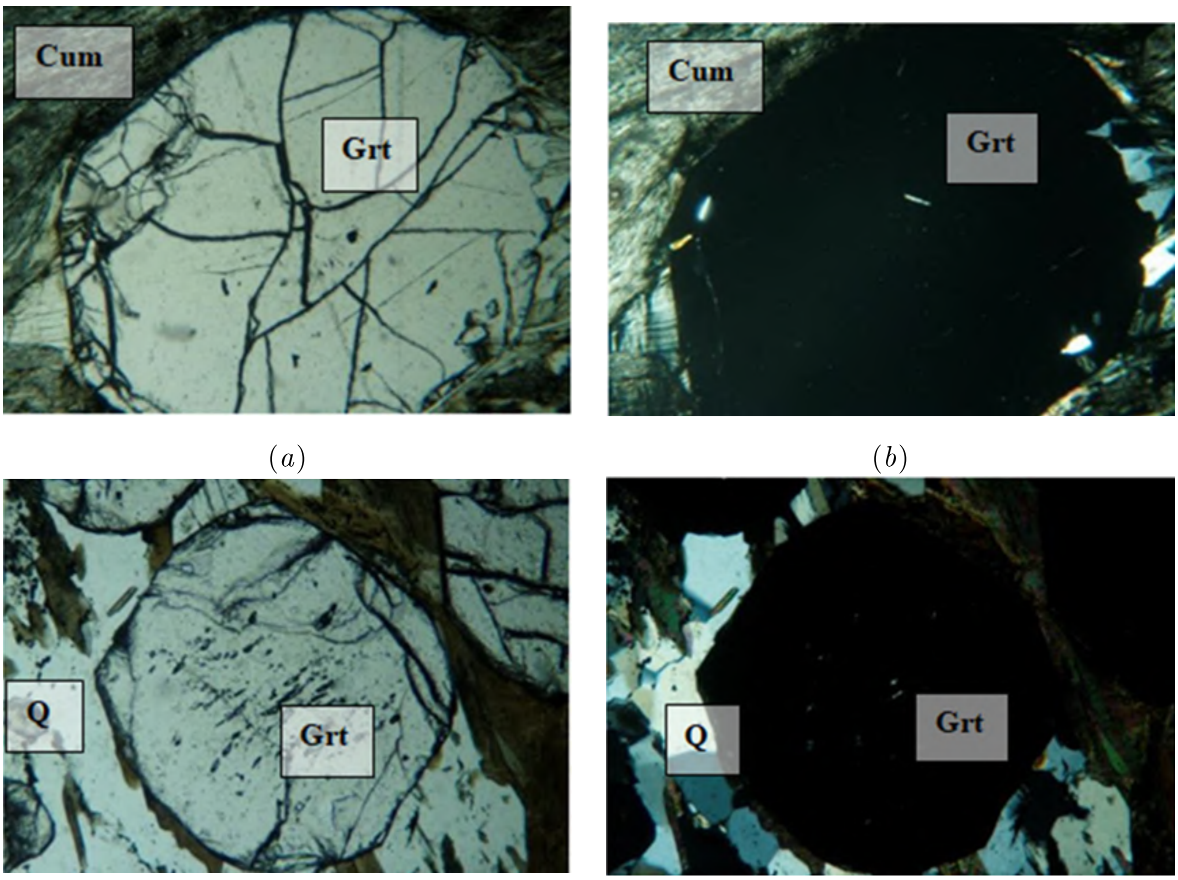
Mineral varieties of garnet-containing shales	Granulometric fractions, mm							Average size of garnet crystals, mm
	-20+5	-5+3	-3+2	-2+1	-1+0.5	-0.5+0	Total	
Type 1	0.0	0.0	7.9	13.1	55.4	23.6	100.0	0.92
Type 2	0.0	6.8	28.4	43.0	18.2	3.6	100.0	1.75
Type 3	0.2	7.1	40.9	39.3	10.8	1.7	100.0	2.14
Type 4	5.6	20.7	36.4	25.1	9.9	2.3	100.0	5.59
Type 5	19.1	35.9	24.7	11.0	7.5	1.8	100.0	3.68

from the centre of the shale horizon to the periphery (its contact with the ferruginous horizon). In the parts of the shale horizon in contact with the ferruginous horizon, metamorphism was accompanied by an active exchange phenomenon – bimetasomatism [4, 5], which contributed to the growth of large garnet crystals. For cummingtonite-garnet-quartz-biotite and garnet-quartz-biotite-cummingtonite schists located in the contact zones, large (15-20 mm) xenomorphic fractured crystals are often found, which most often form granoblast aggregates.

Differentiation of garnet individuals by size is observed in shale layers of different mineral composition. Microscopic studies have also shown that quartz layers are characterised by much smaller garnet crystals than the adjacent biotite and muscovite-biotite layers. This is due to different growth kinetics of garnet crystals. In the apopiskovik or apoaleurolytic quartz layers, the growth of garnet crystals was difficult compared to the apopelitic silicate layers, within which the nutrient solutions and mineral formation conditions were more optimal for garnet crystals. This tendency is observed for all the identified mineral varieties of garnet-bearing shales of the Hannivske deposit.

The composition of mineral aggregates surrounding garnet individuals will have a different impact on the further processing technology of garnet-bearing shales of the Hanna deposit [7]]. Based on the results of detailed microscopic determinations, it was found that the most common minerals surrounding garnets are biotite, cummingtonite, muscovite and quartz and their combinations (figure 4).

In the further processing technology, the environment of biotite and muscovite will be the most favourable due to the fact that garnet grains will be easily leached from the mica matrix



(*a*) (*b*)

(*c*) (*d*)

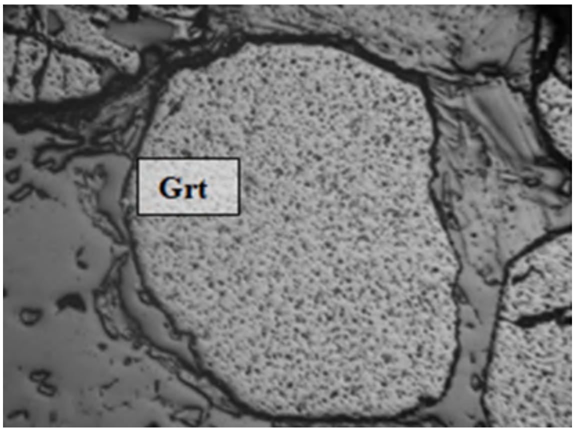
Figure 4. Inclusions of garnet individuals surrounded by various minerals from the garnet-bearing shales of the Gannisky deposit: transmitted light; without the analyser (*a, c*) and with the analyser (*b, d*); 35x magnification. Grt – garnet; Cum – cummingtonite; Q – quartz.

during crushing and grinding. In the environment of cummingtonite, garnet individuals are more difficult to remove. Fine-grained quartz aggregates will reliably retain garnet individuals during ore preparation operations.

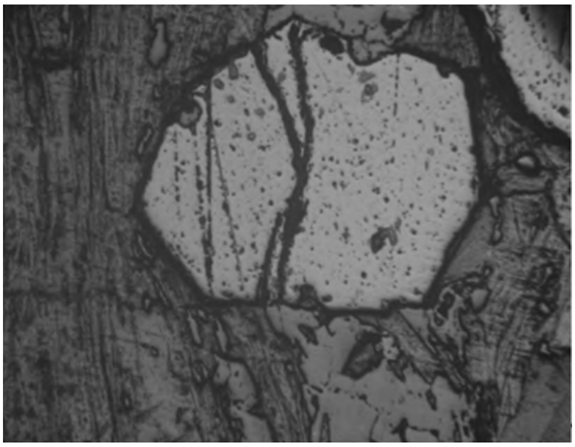
Anatomy of garnet crystals. Microscopic examination of garnet-bearing shales from the Hannivske deposit in reflected and transmitted light revealed that garnet individuals have different levels of defectiveness (fracture). Along with whole, non-cracked crystals, the bulk of the crystals in the rock of all mineral varieties are cracked to some extent (figure 5). 23% of garnet individuals are non-cracked, 27.6% are slightly cracked, 14.0% are moderately cracked, 13.7% are heavily cracked and 21.7% are very heavily cracked. Thus, about 50% of garnet crystals are non-cracked and slightly cracked.

Microscopic studies also revealed that a significant number of garnet individuals contain small (0.01-0.25 mm in size) inclusions of ore and nonmetallic minerals. The ore minerals are most often represented by magnetite (figure 6), non-metallic quartz (figure 7), cummingtonite and biotite (figure 8).

Magnetite most often forms single xenomorphic inclusions 0.01-0.1 mm in size in the middle



(*a*)



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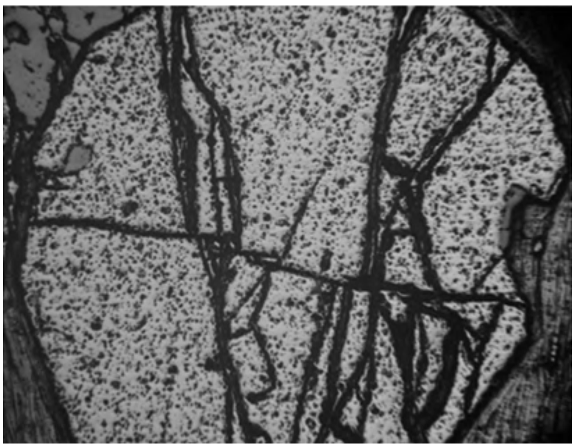

(*c*)

(*d*)

Figure 5. Individuals of garnet without cracks (*a*) and with small (*b*), medium (*c*) and large (*d*) cracked structure from garnet-bearing shales of the Gannivske deposit. Reflected light; without analyser; 35x magnification. Grt – garnet.

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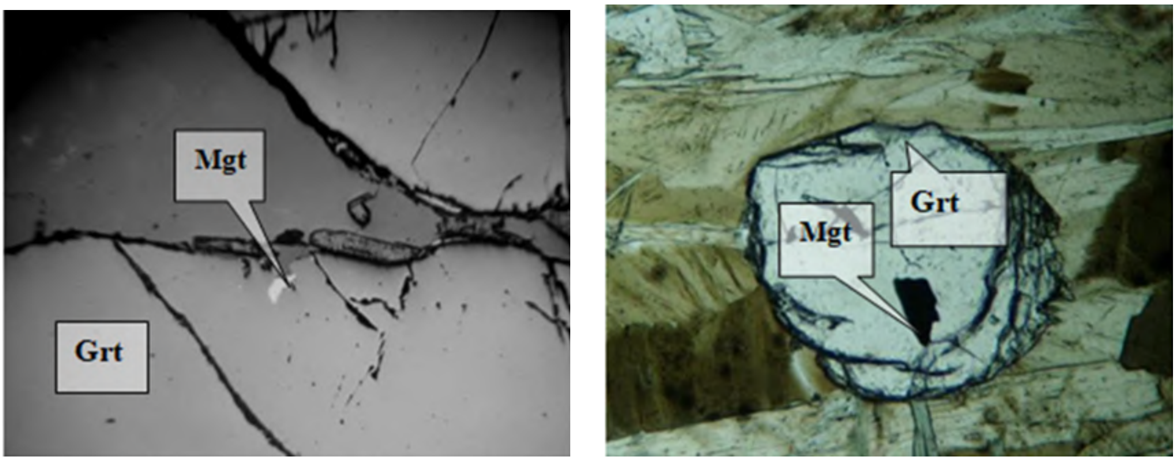
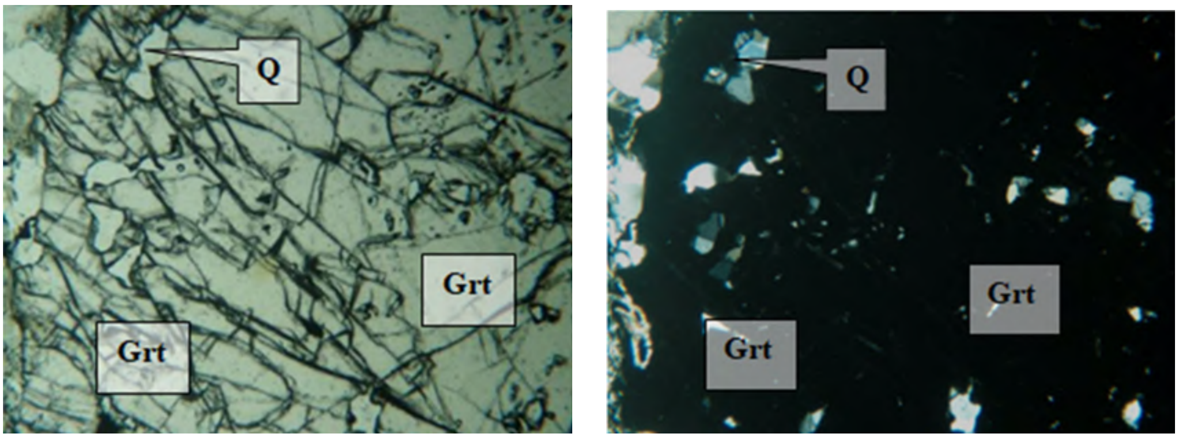
of garnet individuals; quartz, similar to magnetite, occurs as separate inclusions, sometimes forming thin veins (figure 7c, d); biotite and cumingtonite – as personified individuals (figure 8). During mineralogical studies of garnet-bearing schists, it was found that in garnet individuals, the most common non-metallic inclusions are quartz. Some garnet individuals are found almost without inclusions of ore and nonmetallic minerals.

The colour of garnet grains depends on the fluctuations in the shade of individual garnet individuals in the range from black to pink, as well as on the inclusions of other minerals (polychrome and uniformity of colour) [9, 12]. The polychromaticity of individual garnet individuals in the garnet-bearing schists of the Hanna deposit is mainly due to inclusions of other minerals. As a result of macroscopic and microscopic studies of shales, it was found that black and dark green colour within individual garnet individuals is due to inclusions of



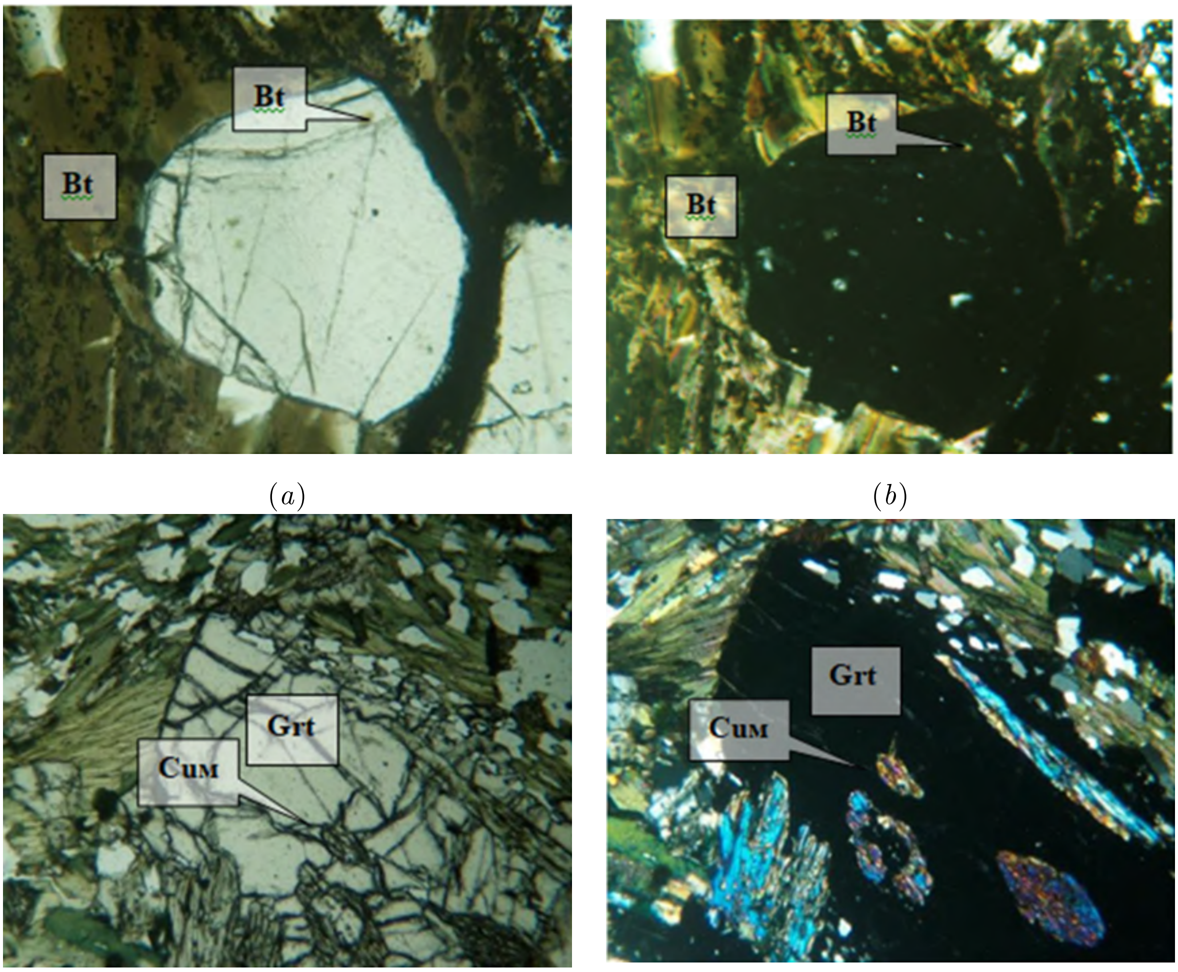
(*a*) (*b*)

Figure 6. Inclusions of ore (magnetite) minerals in garnet individuals from garnet-bearing shales of the Gannivske deposit. Reflected light (*a*) without analyser and transmitted light (*b*) with analyser; magnification 35x. Grt – garnet Mt – magnetite; Bt – biotite.



(*a*) (*b*)

Figure 7. Xenomorphic inclusions (quartz within garnet individuals from garnet-bearing shales of the Gannisky deposit: transmitted light; without analyser (*a*) and with analyser (*b*); magnification 35x. Q – quartz; Grt – garnet.



(a) (b) (c) (d)

Figure 8. Inclusion of non-metallic minerals (biotite and cummingtonite) in garnet individuals from garnet-bearing shales of the Gannisky deposit; transmitted light; without analyser (*a, c*) and with analyser (*b, d*); 35x magnification. Grt – garnet; Cum – cummingtonite; Bt – biotite.

magnetite, biotite and cumingtonite. The identified individuals and quartz vein aggregates do not significantly affect the colour of garnet individuals.

According to the results of previous studies [10], the chemical composition of garnet was determined, which is similar in composition to almandine with impurities of pyrrhotite and spessartine minerals. The content of pyralspethite mineral (the total molecular content of almandine, pyrrhotite and spessartine) in garnet from the Hanna deposit varies from 87 mol% to 99 mol%. According to the technical specifications, the content of pyralspeth mineral should be at least 80-90%. Therefore, the garnets from the studied garnet-bearing shales significantly exceed this indicator.

The microhardness of garnets is an important characteristic that determines their technological application. Highly ferruginous garnets with a high proportion of almandine mineral, whose microhardness value is more than 1400 kgf/mm^2, are suitable as abrasive raw materials [13]. The microhardness values of garnet individuals from the studied shales range from 1477 to 1597 kgf/mm^2 (table 3). The highest values of microhardness were found for garnets of the fourth type of shale, and the lowest – for the first type.

Table 3. Average microhardness values of garnets from different shales of the Hannsvka deposit.

Mineral varieties of garnet-containing shales	Interval of values, kgf/mm^2	Average, kgf/mm^2
Type 1	1411-1496	1477
Type 2	1438-1507	1489
Type 3	1519-1592	1563
Type 4	1523-1617	1597
Type 5	1495-1527	1514

In terms of microhardness, the studied garnets meet the technical requirements for abrasive raw materials.

4. Conclusions

1. Garnet-bearing shales are part of the rocks of the first and zero shale horizons that underlie the productive iron ore strata of the Gannivske deposit. Garnet is similar in composition to almandine with impurities of pyrope, andradite, and spessartine minerals.
2. The garnet-bearing shales of the Gannivske deposit are considered as a possible promising raw material for the production of garnet concentrate.
3. In the early 80s of the twentieth century, the reserves of garnet-bearing shales within the project contour of the Hannivskyi open pit were estimated at 150 million tonnes, and currently the resources of garnet-bearing shales are about 1 billion tonnes.
4. The garnet-bearing shale horizons, which were metamorphosed in the epidote-amphibolite facies, are characterised by mineralogical zonation. There are several mineral varieties of garnet-bearing shales, the average garnet content in them varies from 1-2 to 15-25 vol.
5. Depending on the position in the horizon, garnet-bearing shales of the zero and first shale horizons contain garnet crystals that differ sharply in morphology and anatomy, composition, and properties.
6. The average size of garnet crystals naturally increases from staurolite-muscovite-quartz-biotite schist (mineral type 1), with the average size of garnet individuals being 0.92 mm, to garnet-quartz-biotite-cummingtonite schist (mineral type 5), with the average size of garnet crystals reaching 3.68 mm.
7. Crystallomorphological studies of garnets from the material of the initial samples allowed us to distinguish two main habit forms: tetragon-trioctahedron and rhombododecahedron. The tetragon-trioctahedron habit form prevails. The combination of the rhombododecahedron and tetragon-trioctahedron shapes gives garnet crystals an isometric appearance that is close to spherical. This should be taken into account when developing the technology for the production of pomegranate concentrate.
8. The crystals of the main rock-forming minerals (cumingtonite, biotite, quartz) in shale have completely opposite shapes – cumingtonite is characterised by a columnar appearance, muscovite and biotite by a lamellar appearance, quartz often forms irregular xenomorphic formations in the main shale fabric.
9. The majority of garnet individuals (77%) are fractured. Increased fracturing will cause crystals to be reworked during ore preparation operations and a significant part of garnet crystal fragments to become a fine-grained fraction. This factor will significantly impair the recoverability of shale and cause an increase in the content of the garnet component in the beneficiation waste.

10. The most common minerals surrounding garnet individuals are biotite, cummingtonite, muscovite and quartz. When developing a technology for the beneficiation of garnet-containing shales, it is necessary to provide for their removal from intermediate products.
11. Based on the results of detailed mineralogical studies, it is possible to predict the possibility of producing garnet concentrate from garnet-bearing shales. Technological indicators of beneficiation can be determined after special studies.
12. The study of pomegranate-bearing shales of the Hannivske deposit is due to the possibility of producing pomegranate concentrate. It is used in many industries due to its high hardness (7.5-8 Mohs), abrasiveness, density (4000-4500 kg/m3), physical and chemical homogeneity and stability, non-toxicity and inertness in a wide pH range, and the ability to split into particles with sharp cutting edges during grinding. The following applications are possible for garnet concentrate, which can be obtained from garnet-bearing shales of the Hannivske deposit
    – as an abrasive (powders, bars, skins, material for sandblasting surfaces);
    – for waterjet cutting of various materials;
    – as a powder coating;
    – as a material for water filtration;
13. In order to consider the possibility of introducing the processing of garnet shale during the development of the Hanna quarry in the north-eastern direction, the following can be recommended: detailed exploration of garnet shale deposits, calculation of their reserves, economic assessment of the feasibility of their extraction, obtaining a development permit, and conducting pre-project studies.

Further areas of research include technological studies of pomegranate concentrate extracted from the garnet-bearing shales of the Hannivske deposit in the Kryvyi Rih iron ore basin.

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Paleogeomorphological amber traps of the prypiat amber-bearing basin of the Ukraine (theory and methodology of searches)

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Abstract. Ukraine's amber industry requires expansion of its mineral resource base. The territory of the Prypiat amber basin (PAB) is considered to be the most promising for this purpose. Here, a prognosis and search system for amber (PSSA) has been created that is capable of solving current problems of the industry and its development on a scientific basis, including the concept of the amber-bearing formation (AF) and its practical implementation – the search for the amber-bearing objects (AOs) – traps of various genesis. Currently, it is believed that the main increase in amber production in the territory of the PAB will occur due to paleogeomorphological traps (PTs). This task is solved by the morphochronodynamic concept, the information and methodological basis of which is paleogeomorphology. The morphochronodynamic concept uses the methodology of systems theory, presents its own research method and determines the content of subject cartographic models that reflect the results of the research. These are maps of: paleogeomorphological cycles of development of the geomorphosystem of the time of the AF formation; statics and dynamics of its materialised space-time – the geomorpholithosphere. On their basis, the paleogeomorphological traps of the PAB territory were typified by rank and their general assessment was made to identify increased, primarily industrial, concentrations of amber. The first rank is the geomorpholithosphere of the time of the AF formation, the second rank is its structural elements and, at the same time, forecasting and prospecting units – historically-dynamic basin geomorphosystems. The third rank includes morpholithohorizons of the geomorpholithosphere (elements of its vertical structure) and morpholithocomplexes (elements of its horizontal structure) that are promising for amber deposits. A comprehensive analysis of paleogeomorphological maps of the cycles of geomorphosystem development and formation of the AF allows to distinguish the fourth and fifth ranked PTs in the territory of the PAB. The fourth rank includes some forms of palaeo-relief of perspective cycles (ancient valleys, coastal zones, uplands). The fifth rank includes parts of large forms – depressions in paleodolines, beaches, benches, etc.

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1. Introduction

The Prypiat Amber Basin (PAB) is the only operating industrial basin in Ukraine, the development of which allows us to expand the mineral resource base of the amber industry. The prognosis and search system for amber (PSSA) allows us to solve current problems and develop the industry. The theoretical basis of the PSSA is the idea of a geological amber-bearing formation (AF). Practically, the most important elements of the AF are amber-bearing objects (AOs) or traps. There are genetic types of amber traps: stratigraphic, lithological, tectonic, geomorphological, paleogeomorphological, and combined [1–3]. A significant increase in amber production in the PAB is possible due to the discovery of paleogeomorphological traps (PTs). This allows for a comprehensive analysis of large-scale paleogeomorphological maps of the AF formation cycles, as well as maps of the statics and dynamics of the geomorpholithosphere of the PAB territory.

2. Methods and materials

The methodology of the general theory of systems, a set of geological, geomorphological, paleogeographical, paleogeomorphological methods, and the results of laboratory amber study were used in the work. The obtained results were presented in tables, displayed on graphs, general and special maps, geological and geomorphological sections. Traditional paleogeomorphological maps of reconstructed paleoreliefs of Cenozoic cycles of development of the geomorphosystem of the time of the AF formation, special maps of statics and dynamics of the geomorpholithosphere were also studied. Maps of statics – composition, complexity, structure; maps of dynamics – evolutionary-dynamic zones, functional-dynamic zones, which show the correlation of processes of initial (destruction), transit, terminal (accumulation), restructuring of the geomorphosystem during the Mesozoic-Cenozoic and its individual segments. The results of the authors' own research, obtained in the course of research work amber in Ukraine on, as well as the implementation of international projects (in particular, joint projects with the Republic of Poland: "Amber Roads: Formation of deposits – extraction. Scientific and methodological foundations, rational use"; "Amber deposits and their characteristics"). Materials of "Geoinform" and geological expeditions of the Ukrainian geological company were used.

3. Paleogeomorphological reconstructions and results

The searches for the PP are carried out on the basis of the morphochronodynamic concept of geomorphology, the information and methodological basis of which is paleogeomorphology [4, 5]. The morphochronodynamic concept is based on its own comprehensive research method that combines geological, geophysical, geomorphological, paleogeographic, cartographic, mathematical and other methods. Paleogeomorphology studies the ancient stages of development of the Earth's morphosystem, the results of which are shown on paleogeomorphological maps. There are 2 types of paleogeomorphological maps: ancient buried relief, which exists in real time; paleogeomorphological maps of the restored reliefs of ancient cycles (stages) of geomorphosystem development. The morphochronodynamic concept allows to create special maps (statics, dynamics) of the geomorpholithosphere and to carry out on their basis a cross-cutting forecast of material movements, energy transformations, information transfers in the geomorpholithosphere of the past (retrospective forecasting), present (actual forecasting), and future (prospective forecasting). The developed methodological algorithm for the use of both types of paleogeomorphological maps allows for more efficient and rational prospecting for various minerals (including amber). This made it possible to distinguish different types of PTs, which form a certain hierarchy (ranks), and to make predictions about the detection of increased concentrations of amber (and industrial value) in them. When typing the traps, we took into account works [6–9].

The *first rank* of the PTs is a part of the geomorpholithosphere of the time of formation of the AF of the PAB territory.

The *second rank* is historically-dynamic basin geomorphosystems – structural elements of the geomorphosystem (geomorpholithosphere), which are also the forecast and search units of the PSSA of the PAB territory.

The *third rank* is the morpholithic horizons of the geomorpholithosphere of the time of the AF formation, as well as elements of its vertical structure. This rank can also include morpholithocomplexes – elements of the horizontal structure of the geomorpholithosphere that are "filled" with morpholithohorizons. In this case, morpholithohorizons and morpholithocomplexes are important, as they are promising for the discovery of amber deposits. First of all, these are Paleogene morpholithohorizons. The Neogene and Quaternary morpholithohorizons may also contain amber deposits, but they are repeated (redeposited) and inferior to the primary deposits of the Paleogene morpholithohorizons.

The following ranks (fourth and fifth) are identified using traditional paleogeomorphological maps of restored paleoreliefs, prospective for amber deposits, stages of geomorphosystem development, and maps of the geomorpholithosphere statics and dynamics.

The *fourth rank* is formed by large forms of palaeorelief – ancient buried valleys, uplands, plateaus, deltas, and cones of deposition.

The *fifth rank* of the PTs can be independent or have a historical and genetic connection (be part of) large palaeorelief forms (within the PAB these are cones of deposition, abrasion-accumulative benches and beaches).

The PAB is crossed by 12 historically-dynamic basin geomorphosystems located on the Ukrainian shield, Volyno-Podolskya plate and directed to the Prypiatskaya depression and the Luginskaya historically-dynamic basin geomorphosystem, which opens into the Dniprovsko-Donetskaya depression.

Within the PBB, the Nihovyshchenska, Khmelnytsko-Stepanska, Zvyahilsko-Dubrovytska, Snovydovytska, Kupilska, Olevska, Horodetska, Luchenkivska, Zhelonska, Rudnenska, Vystupovichska, Denysovychska geomorphosystems are located from west to east (figure 1).

We studied the area, configuration in plan, exposed surface (orohydrography, topography), position, lower buried surface (relief, composition and age of rocks), thickness and shape (symmetry, anisotropy) of the morpholithobodies of the basin geomorphosystem, neighbourhood,

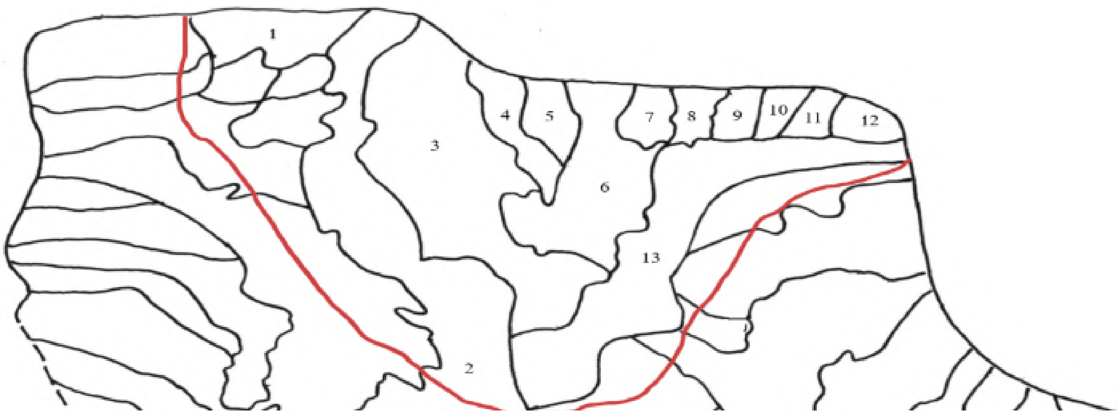

Figure 1. Prypiat amber basin. Historically and dynamic basin geomorphological systems: 1. Nihovyshchenska, 2. Khmelnytsko-Stepanska, 3. Novohrad-Volynsko-Dubrovytska, 4. Snovydovytska, 5. Kupelska , 6. Olevska, 7. Horodetska, 8. Luchenkivska, 9. Zhelonska, 10. Rudnenska, 11. Vystupovichska, 12. Denysivska, 13. Luginska.

boundaries, vertical (distribution, thickness, lithology of morphological zones) and horizontal (composition, complexity, areas of morphological complexes) structure, conformity of exposed and buried surfaces, valley formation of historically-dynamic basin geomorphosystems. Their quantitative and qualitative characteristics (coefficients) were calculated, which together show their positionality, metrics, composition, structure, historical, evolutionary, and functional dynamics.

Historically-dynamic basin geomorphosystems differ in various metrics: area size; length; width; power; symmetry, anisotropy, volumetric shape, external shape of their morpholithobodies; nature of neighbourhood, system boundaries; height differences of the exterior surface, lower boundary and interior surfaces. In terms of plan, the form of historically-dynamic basin geomorphosystems is characterised by the coefficients of elongation (ratio of the average width and length), proportionality (ratio of the actual lengths of thalweg and interfluve lines) and tortuosity (ratio of the directed length of the interfluve to the actual length).

The composition of the systems is characterized by morpholithohorizons. Historically-dynamic basin geomorphosystems differ in composition, interrelationship and spatial differences of morpholithohorizons, which characterize their structure. In the vertical structure of the geomorpholithosphere of the territory of the PAB, there are 9 morpholithohorizons (2 – Jurassic, 2 – Cretaceous, 2 – Paleogene, 2 – Neogene and Quaternary), which occupy different areas. Their spatial relationship is characterized by interbeddedness, thrusting and nesting. Overlaps are widespread, while nesting and adjacency are less common. The horizontal structure of the systems is characterized by morpholithocomplexes that differ in complexity (number of morpholithohorizons). The complexity is always maintained or increases in the direction of the mouth. An indicator of the structure is the plasticity of the surfaces of morpholithohorizons, which is determined by the combination of concave, convex and straight sections. The total information content of the plasticity of buried surfaces relative to the exposed one is expressed by the integral indicator, which characterizes the internal shape, which can be straight (the plasticity of the majority of surfaces is the same), inverted (the plasticity of most of the exposed surfaces is opposite to the exposed one) and semi-inverted (the plasticity of the exposed and exposed surfaces are equally the same).

The structure of historically-dynamic basin geomorphosystems can be expressed by volumetric-planers (morpholithocomplexes) and linear-pointer elements. According to the ability to transmit material and energy flows, morpholithocomplexes are divided into through (composed of bedrock with vertical water movement in them) closed (composed of hard rocks and no water movement in them) and transitory (composed of permeable and hard sediments and predominantly horizontal water movement in them). This is complemented by data from the valley formation in historic-dynamic zones: active, less active, and free of movement. In historically- dynamic basin geomorphosystems, the most active are functionally valley formations, which are characterized by different valley coefficients – general (ratio of the length of all valleys to the basin area) and more than 20 partial (ratio of the length of valleys of individual cycles to the basin area). The total coefficient of valley formation of the historically-dynamic basin geomorphosystems of the PAB is 0.01-0.4.

Statics reflects the current dynamics – the currentness of functional, historical and the historically-dynamic basin geomorphosystems. The dynamic analysis of statics indicators is carried out using the methods of systematic analysis, analogies (extrapolations), and correlation analysis. The directions, intensity, and nature of the movement of the matter-energy are reflected in the following indicators of symmetry, anisotropy, and the volumetric shape of the morpholithobodies. Larger deviations from symmetry (partial symmetry, asymmetry) also indicate a greater dynamical potential of the system, while pronounced anisotropy indicates directions. The opposite is evidenced by the developed symmetry, not pronounced anisotropy, flat and complex forms. The planer form of the themes is expressed by the coefficients of elongation, prominence, and sinuosity. Their widening towards the mouth and straightness enhance transit, sounding, tortuosity and vectors – the accumulation of matter and energy. Predicting the current (and past) vertical and lateral changes of matter and energy in systems allows us to make a comparative analysis of internal and external shape maps. Complex neighbourhoods, interconnections of morpholithobodies of systems show changes in the directions of flows, isolated areas, and places of accumulation of potential energy. The overlapping of morpholithohorizons and their straight plastic bounding surfaces indicate a displacement, while nesting and sheltering, concave and convex surfaces indicate accelerated movement, as well as the accumulation of matter and energy. A symmetry analysis of the long-term distribution of morpholithocomplexes by complexity and composition indicates trends in their development, and their metrics, positionality and permeability of morpholithocomplexes to matter and energy flows (through, transit, closed) – the current functional dynamics of historically-dynamic basin geomorphosystems. The linear-pointer structural elements of the systems directly show their modern and historical functional dynamics, intensity and directions of movement of matter and energy. Figures 2, 3, and 4 show the maps of statics and dynamics of the geomorpholithosphere of the PAB territory.

The analysis of paleogeomorphological maps of the PAB area shows that at the end of the Cretaceous, the seas transgressed and the area rose sharply. In the early Eocene, new

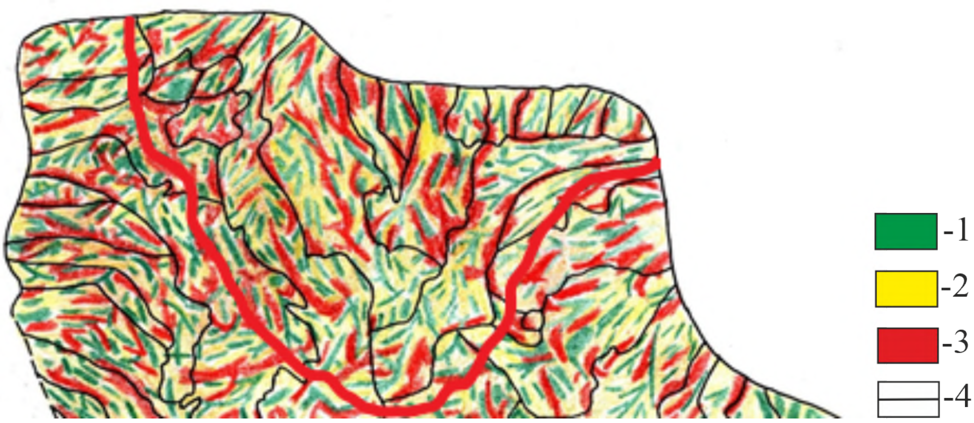

Figure 2. Evolutionary and dynamic zones of historicaly-dynamic basin geomorphosystems.

Figure 3. Functional and dynamic zones of historicaly-dynamic basin geomorphosystems.

Figure 4. Functional and dynamic zones of historical and dynamic basin geomorphosystems.

depressions occurred: 50-80% of the area is occupied by denudation-accumulation plains and 15-25% by denudation plains. After a slight uplift in the early Eocene-Oligocene cycle (P2-3), marine transgression gradually expanded into the PAB. Large terminals appeared everywhere. At the beginning of the Miocene cycle (N1), the area was dominated by a denudation-accumulation plain. In the Miocene-Pliocene cycle (N1-2), the area of the coastal-marine and mixed accumulative plains changed. In the Quaternary cycle (Q), active differential tectonic movements, emergence of large areas of denudation and accumulation, intensification of transit processes, emergence of new flow directions, river bifurcations, lake and marsh transgressions, and glaciation are observed in the PAB (figure 5, 6).

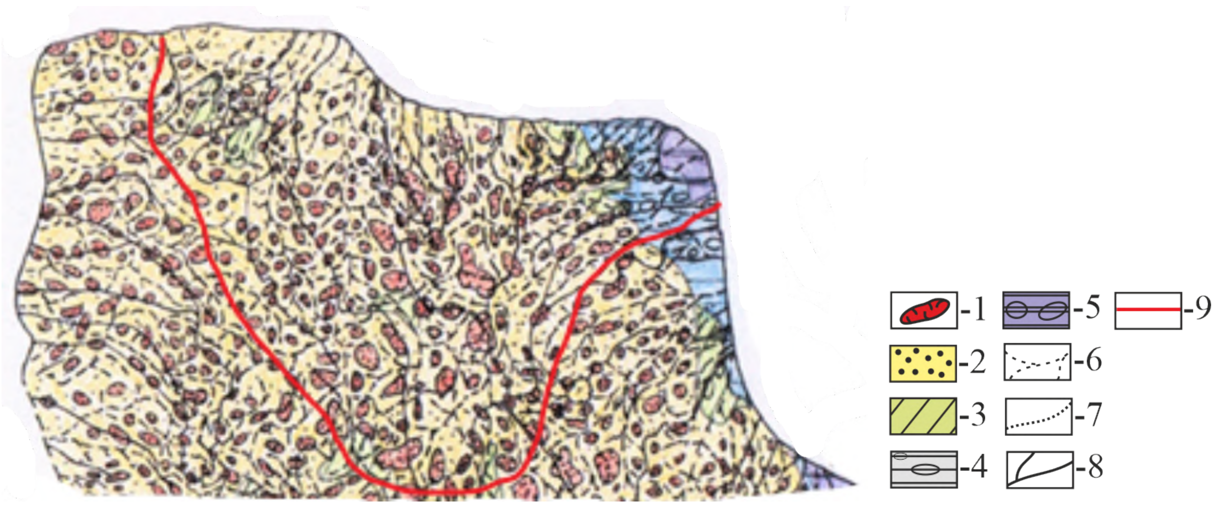

Figure 5. Paleogeomorphological map of the Paleocene-Middle Eocene stage of the development of the territory: 1 – denudation relief, 2 – denudation-accumulative and accumulative-denudation relief, 3 – accumulative relief of the coastal plain, 4 – abrasive-accumulative relief of the shallow sea with islands and raised seabed areas, 5 – accumulative relief of the relatively deep sea with islands and elevated seabed areas, 6 – thalwegs of continental and submarine paleodolines, 7 – watershed lines, 8 – boundaries of historical and dynamic basin geomorphosystems, 9 – boundaries of the Prypiat amber basin.

Figure 6. Paleogeomorphological map of the Late Eocene-Middle Oligocene stage of the development of the territory: 1 – denudation relief, 2 – denudation-accumulative and accumulative-denudation relief, 3 – accumulative relief of the coastal plain, 4 – abrasive-accumulative relief of the shallow sea with islands and raised seabed areas, 5 – accumulative relief of the relatively deep sea with islands and elevated seabed areas, 6 – thalwegs of continental and submarine paleodolines, 7 – watershed lines, 8 – boundaries of historical and dynamic basin geomorphosystems, 9 – boundaries of the Prypiat amber basin.

In the historically-dynamic basin geomorphosystems, during the stages of formation of the AF, the boundaries and integrity were violated, the conditions, types of exogenous morpholithogenesis, and the correlation of denudation, transformation and accretion processes changed. They, especially the adjacent ones, are developing simultaneously. According to the peculiarities of evolutionary dynamics, relatively stable and unstable systems are distinguished within the PAB. Their central element is the zone of consolidated negative forms, which occupies 10-40% of the area. In plan, it has an elongated (straight, arcuate, sinuous) and isometric configuration. The zone of internal basement alterations (20-70% of the area) is of a planer distribution and is more common in the internal part of the systems. The zone of inter-basin alterations (15-65% of the area) is represented by straight, arc, circle, often sinuous strips that coincide with the boundaries, cross them and divide the systems.

Most systems have a certain percentage of newly formed boundaries, which are primarily of tectonic nature. Distributions of denudation, transit and accumulative landforms reflect the distributions of the initial, transit and terminal functions of the systems. Denudation forms, which are found everywhere and occupy 10-25% of their area, indicate the initial nature of the systems. The places of increased density of morpholthohorizons are terminal. They are sub-parallel, intersecting, and multi-story. Terminality can be quantified on statics maps. In geomorphosystems, terminals often occupy more than half of the area. The absolute measure of transitivity is the total mass of sediments. The transitivity expresses the composition of the morpholithocomplexes, and for the whole system, the development of the valley formation, which expresses the valley coefficient.

Functional dynamics in historically-dynamic basin geomorphosystems is carried out due to stable groupings of morpholithocomplexes, through which the substance moves from and to them. During the Mesozoic-Cenozoic, historically-dynamic basin geomorphosystems determined the established directions and channels of substance movement. According to the ratio of dissipative functions in the systems, they are divided into groups. The following groups are

Table 1. Paleogeomorphological traps and amber bearing capacity of historical and dynamic basin geomorphosystems of the geomorpholithosphere (first rank) of the Prupyat amber-bearing basin (PAB).

Second rank	**Third rank**	**Fourth rank**	**Fifth rank**	**Description**
Historically-dynamic basin geomorphosystems (number on the maps) and amber bearing capacity in their areas (h – high, m – middle, l – low)	morpholitho-horizons (number)	morpholitho-complexes (complexity – number of morpholitho horizons)	large buried forms of palaeorelief	parts of large buried forms
Nihovyshchenska (1)	4	4, 3, 2, 1	ancient valleys	abrasive-accumulative benches of islands
Khmelnytsko-Stepansivska (2)	4	4, 3, 2, 1	ancient valleys	abrasive-accumulative benches of islands
Zviahelsko-Dubrovytska (3)	4	4, 3, 2, 1	ancient valleys	abrasive-accumulative benches of islands
Snovydovychska (4)	4	4, 3, 2, 1	ancient valleys	abrasive-accumulative benches of islands
Kupilska (5)	4	4, 3, 2, 1	ancient valleys	abrasive-accumulative benches of islands
Olevska (6)	4	4, 3, 2, 1	ancient valleys, plateaus, uplands adjacent to the coastline, large river deltas	thalwegs and depressions of ancient valleys; places of confluence and confluence of tributaries; cones of ravines from plateaus and uplands; abrasive-accumulative benches of islands
Horodetska (7)	4	4, 3, 2, 1	ancient valleys	abrasive-accumulative benches of islands
Luchynska (8)	4	4, 3, 2, 1	ancient valleys	thalwegs and valley depressions, gully cones, abrasive-accumulative benches of islands
Zhelonska (9)	9	7-9, 5-6, 4, 2-3	ancient valleys	thalwegs and valley depressions, gully cones, abrasive-accumulative benches of islands
Rudnenska (10)	9	7-9, 5-6, 4, 2-3	ancient valleys	thalwegs of valleys, abrasive-accumulative benches of islands
Vystupovichska (11)	9	7-9, 5-6, 4, 2-3	ancient valleys	thalwegs of valleys, abrasive-accumulative benches of islands
Denysivska (12)	9	7-9	hills adjacent to the coastline	abrasive-accumulative benches adjacent land
Luginska (13)	9	7-9, 5-6, 4	valleys adjacent to the coastline of the upland	thalwegs and depressions of ancient valleys, places of confluence and confluence of tributaries – “twins”, “tees”; cones of ravines from plateaus and hills

characteristic of the PAB: 1) intensive, directional transit, subordinate terminal development, no significant changes (5 systems); 2) uneven in intensity directional transit, well-developed terminals, no significant changes (5 systems); 3) intensive but unrestricted transit in directions, different terminal development, significant changes (3 systems).

Table 1 presents the most important information from the paleogeomorphological maps of the cycles (stages) of the geomorphosystem development during the formation of the AF and maps of the statics and dynamics of the geomorpholithosphere (first rank of PTs) of 13 historical and dynamic basin geomorphosystems (second rank of PTs) in relation to PTs of the third, fourth and fifth ranks. On the basis of these and direct prospecting data, their amber bearing capacity was estimated on a relative scale (h-high, m-middle, l-low). The geomorphosystems may be dominated by the 1 or 2 and 3 variants of amber bearing capacity.

4. Conclusions

The amber industry of Ukraine requires expansion of the mineral resource base. The most promising for this purpose is the territory of the PAB. For this purpose, a forecasting and prospecting system for amber has been created, the practically important elements of which are the AOs or traps of various genesis. The main increase in amber production will take place in the territory of the PAB due to the use of Pts. The search for the PT should be carried out at the modern scientific level, which is provided by the morphochronodynamic concept of geomorphology, the main methodological and informational-methodical element of which is paleogeomorphology. A methodical algorithm for the combined use of cartographic models of the geomorphosystem (paleogeomorphological maps of certain cycles of its development, statics and dynamics of its materialized space-time – geomorpholithosphere) has been developed, which allowed typifying the PTs by rank. The first rank is the geomorpholithosphere, the second rank is the historically-dynamic basin geomorphosystems as the main regional units of prognostic and prospecting works for amber and other sedimentary minerals, the third rank is morpholithohorizons, which are located in the geomorpholithosphere and are promising for amber placers; the fourth rank is paleorelief forms (ancient buried valleys, plateaus, uplands adjacent to the coastline, large river deltas); fifth rank – parts of large paleorelief forms (elements): thalweg and depressions of ancient valleys; places of confluence and confluence of tributaries – “twins”, “tees”; cones of ravine outflow from plateaus and uplands; abrasive-accumulative beaches (bench). On the basis of the developed typification of paleogeomorphological amber traps, a prognostic and exploratory assessment of 13 historically-dynamic basin geomorphosystems of the PAB territory was made.

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PAPER • OPEN ACCESS

The impact of low-molecular carboxylic acids on carbon dioxide corrosion of steel in underground gas production equipment in the Dnipro-Donetsk basin fields

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The impact of low-molecular carboxylic acids on carbon dioxide corrosion of steel in underground gas production equipment in the Dnipro-Donetsk basin fields

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Abstract. The work carried out a set of experimental studies to reduce the activity of corrosion processes in underground well equipment. Corrosion of downhole equipment is a complex heterogeneous process. In the complex of factors influencing both magnitude and intensity of corrosion damage, low molecular weight water-soluble carboxylic acids play a significant role. The features of metal-carbon dioxide corrosion (CO_2 corrosion) in production well fluid have been established depending on low molecular weight carboxylic acids. It has been revealed that the influence of carboxylic acids in field wells in the initial period of development is reduced to the destruction of protective carbonate films formed as a result of carbon dioxide corrosion of the metal surface. The highest corrosion rate is at the beginning of droplet water condensation since the main factors influencing the corrosion rate (acid concentration and temperature) are greatest at this point. It has been established that the interaction of organic acids with metal occurs in the Dnipro-Donetsk basin fields at the temperature range of 90-110 °C and a depth of 3000-3500 m. The interval of action of organic acids on the metal of tubing pipes depends on the regime constancy and operating time of the well. In constant mode, the effect of organic acids is limited to 100-150 m. The effect of corrosion under the influence of organic acids is especially pronounced in wells where the carbon dioxide content is insignificant. The influence of corrosion products on the process speed has been determined. Iron salts of carboxylic acids, formed as a result of corrosion during condensation of aqueous fluid in a well, are subsequently inhibitors of carbon dioxide corrosion of gas industry equipment.

1. Introduction

One of the main reasons affecting the stability of hydrocarbon raw materials production and transportation is gas industry equipment corrosion [1–4]. The service life of pumping and compressor pipes in some cases is 0.5-1.5 years instead of the planned 10 years. More than 3000 hydrocarbon collection system pipeline failures due to internal corrosion are recorded annually. The accident rate of hydrocarbon collection systems pipelines leads to significant losses in hydrocarbon production and environmental pollution [4, 5].

The introduction of advanced technologies for operational equipment protection helps to reduce labor costs and material consumption and to decrease repair and restoration work carried out at industrial enterprises [6–8].

Downhole equipment corrosion is a complex heterogeneous process. In the complex of factors influencing both magnitude and intensity of corrosion damage, low molecular weight water-soluble carboxylic acids play a significant role [5, 9–11].

2. Problem statement

The mechanism of carbon dioxide corrosion has been studied quite deeply and comprehensively [1–4, 9, 10, 12–14]. The intensity of equipment corrosion destruction in fields where gas contains CO_2 is determined both by the partial pressure of carbon dioxide (with a low content of organic acids) and the temperature at which the corrosion process occurs [2, 14].

As the gas moves through the wellbore, a liquid phase is released. As a result, a three-phase gas flow of gas-water-hydrocarbon is created inside the pipes. The corrosion rate in a three-phase system is mainly determined by the structure and flow regime. The corrosive activity of the medium in a well depends on the ratio of hydrocarbons to water. Intensive corrosion of equipment, according to some researchers, begins when the water content in the well is 0.1%, and then the corrosion rate remains constant, although the water content increases [2, 3, 9].

The presence of the hydrocarbon fraction in aqueous electrolytes has a significant impact on the corrosion process kinetics and nature. The hydrocarbon phase of a heterogeneous medium, practically inert to metal, accumulates an increased amount of H_2S, O_2, and CO_2 compared to the aqueous phase. As a result, thin layers of electrolyte appear on the surface of the corroding metal, where the corrosion process under conditions of free depolarization proceeds at a higher speed than in the volume of the deposit [2, 9, 15].

However, other studies have noted that the presence of a hydrocarbon phase reduces the gas-liquid flow aggressiveness [3].

Corrosive destruction of equipment surface and underground caused by CO_2 and low molecular weight water-soluble carboxylic acids are usually local and have the form of pittings. They are detected in those elements of equipment where there is water accumulation (coupling and flange connections, fittings). Straight sections of pipes outside these connections, as a rule, corrode very little [10, 11, 13, 16]. In addition to corrosion, erosion-corrosion destruction is observed, caused by powerful speeds of the movement of aggressive environments containing mechanical impurities (iron sulfide, sand) [2].

In the wells located at the gas condensate fields, a certain pattern of corrosion and erosion-corrosion destruction distribution is observed. There is virtually no corrosion at the bottom of tubing hangers (TBG). At a certain depth for each deposit, pitting corrosion appears at the lower ends of the pipes. Their intensity, when moving upward, first increases quite sharply, and then remains approximately constant. In the upper part of the pipes, these damages are almost always the most significant [17].

Corrosion processes in a borehole are affected by temperature: high temperatures shift the limit of corrosion damage to the well mouth, and TBG hangers are intensively destroyed [4].

Carbon dioxide corrosion of both pipes and well equipment is predominantly an electrochemical process with the metal anodic dissolution and hydrogen ions reduction at the cathode sections [2–4].

The corrosion forecast helps to select the optimal methods of anti-corrosion protection of wells at different stages of field development, which in turn helps to increase the effectiveness of protective measures, reduce operating costs, decrease the time of both repairs and downtime of wells, and increase the hydrocarbon production volume [5, 9, 13].

Purpose of the study is to identify the effect of low molecular weight water-soluble carboxylic acids on carbon dioxide corrosion of metal in gas production equipment of wells

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in the North-Eastern region of the Dnipro-Donetsk basin.

3. Materials and methods

The rate of both surface and underground well equipment corrosion depends on various factors, the main of which should be considered the aggressive components CO_2 and low molecular weight water-soluble carboxylic acids contained in natural gas. So natural gas, hydrocarbon condensate, formation water and pipe steel have been chosen as the object of the study. In the low molecular weight water-soluble carboxylic acids mixture, the main component is acetic acid, which, therefore, has been taken further for laboratory studies (table 1).

The main component contained in the formation waters of fields of the North-Eastern Ukraine is sodium chloride. Cation content Na^+ reaches 42 equiv.%. Since the concentration of salts in formation and condensation waters varies over a wide range [2, 3, 5], solutions NaCl and CH_3COOH in distilled water of different concentrations (NaCl from 0.0017 to 2 M, CH_3COOH from 0.00083 to 0.5 M) were chosen for model environments of experimental studies.

Table 1. Composition of water-soluble carboxylic acids in the products of wells of gas industry management fields “PoltavaGasVydobuvannya”.

Field	**Average content of organic acids in the mixture**			
	HCOOH	CH_3COOH	CH_3CH_2COOH	$CH_3CH_2CH_2COOH$
Abazivske and Sementsivske	11.0	70	7.0	12.0
Hadiatske	7.0	80	5.2	7.8
Kotelevske	6.0	75	9.0	10.0
Opishnianske	12.0	65	7.5	15.5
Raspashnivske	1.5	96	1.1	1.4
Mashivske	14.0	63	2.5	20.5
Novotroitske	8.0	82	4.7	5.3
Solokhivske	4.5	92	2.3	1.2
Tymofiivske	5.0	77	8.0	10.0
Yablunivske	2.0	88	3.8	6.2

Similar to the real operating conditions of gas industrial equipment, the experiments were carried out in the temperature range from 293 to 373°K. Since the corrosion of gas industrial equipment with the participation of CO_2 and low-molecular carboxylic acids is local with obvious foci of corrosion characterized by pittings, the study of corrosion processes in model environments was carried out mainly by the gravimetric method, namely with the help of witness samples.

The study of the effect of low molecular weight water-soluble carboxylic acids on carbon dioxide corrosion of downhole equipment was carried out on samples of pipe steel grade D in the gas phase, simulating the interval at which the condensation of aqueous fluid began, and in a liquid single-phase electrolyte-hydrocarbon system, simulating the installation (figure 1 [5]). It is a glass vessel into which the test solution was poured and a fluoroplastic cylinder with witness samples and a propeller stirrer was placed.

The cell was connected to an electric motor, which rotated the stirrer. When the stirrer rotated in a fluoroplastic cylinder, circular movements of the liquid were created in laminar mode with a flow speed of 0.3-0.5 m/s. When the stirrer propeller was installed under the bottom of the cylinder, while rotating it at a speed of 1400 rpm. there was a circular motion of the liquid in a turbulent regime. In this case, the flow speed in the area where the witness samples were placed was 7-8 m/s. In addition to the circular motion, there was also a circulation of liquid through the small cylinder due to the creation of irritation when the stirrer rotated.

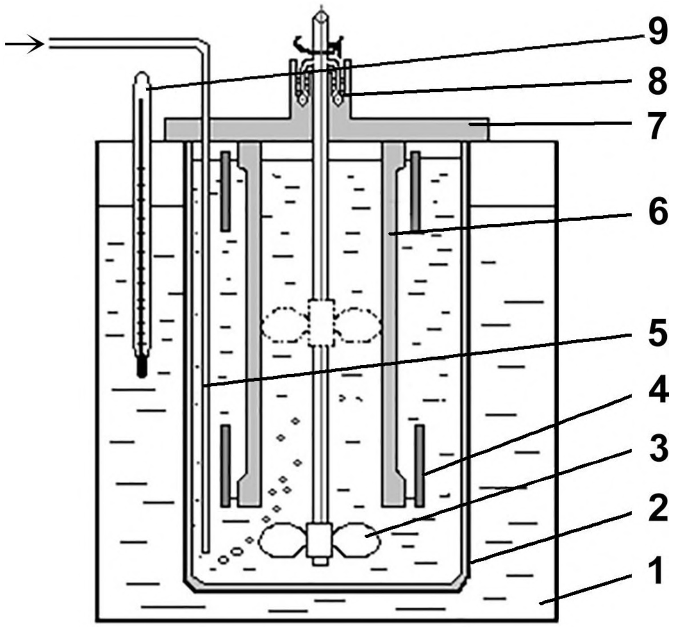

Figure 1. Installation diagram for corrosion research: 1 – thermostat; 2 – glass chamber; 3 – stirrer; 4 – samples; 5 – gas supply tube; 6 – fluoroplastic cylinder; 7 – cover; 8 – hydraulic hole; 9 – mercury thermometer.

The corrosion rate was determined by the loss of metal mass of witness samples placed in the test environment per unit time according to the formula (1) [5]:

$$v = \frac{\Delta m}{S\tau} \tag{1}$$

where v – the corrosion rate of a sample, g/(m^2·h); Δm – weight loss during the study, g; S – sample surface area, m^2; τ – research time, h.

The protective effect of surfactants (Z) was calculated using the formula (2) [5]:

$$Z = \frac{v_0 - v_1}{v_0} 100, \% \tag{2}$$

where v_0 – corrosion rate of the sample without corrosion inhibitor, g/(m^2·h); v_1 – corrosion rate of the sample with corrosion inhibitor, g/(m^2·h).

The measurement results were analyzed using mathematical statistics methods GOST 9.905-82.

Some corrosion studies were carried out in gas fields directly at the wellhead using several methods: gravimetric and iron ion content.

4. Research results

It has been established that the corrosion rate of pipe steel over solutions of acetic acid in CO_2 is the highest 0.35-1.2 g/(m^2·h), in a CO_2 atmosphere over distilled water is the smallest 0.2-0.6 g(m^2·h) (figure 2). No corrosion of steel in an N_2 atmosphere over distilled water was detected during the experiment.

Stabilization of the corrosion rate in the gas phase in the atmosphere CO_2 after a N_2 atmosphere occurs twice as fast (≈12 min.) than in a N_2 atmosphere after CO_2 (≈24 min.) (figure 3).

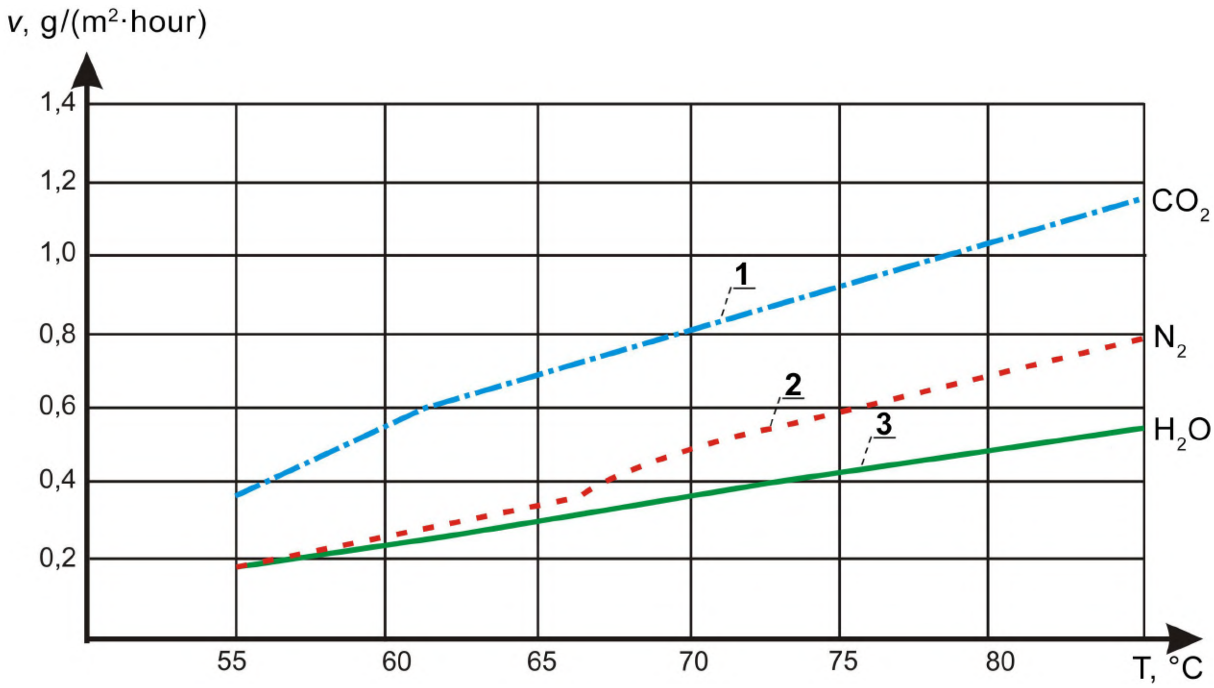

Figure 2. Dependence of the corrosion rate of pipe steel on temperature in a solution that contains 0.5 mol/l NaCl and mol/l CH_3COOH: 1 – in a CO_2 atmosphere; 2 – in a N_2 atmosphere; 3 – in a CO_2 atmosphere over distilled water.

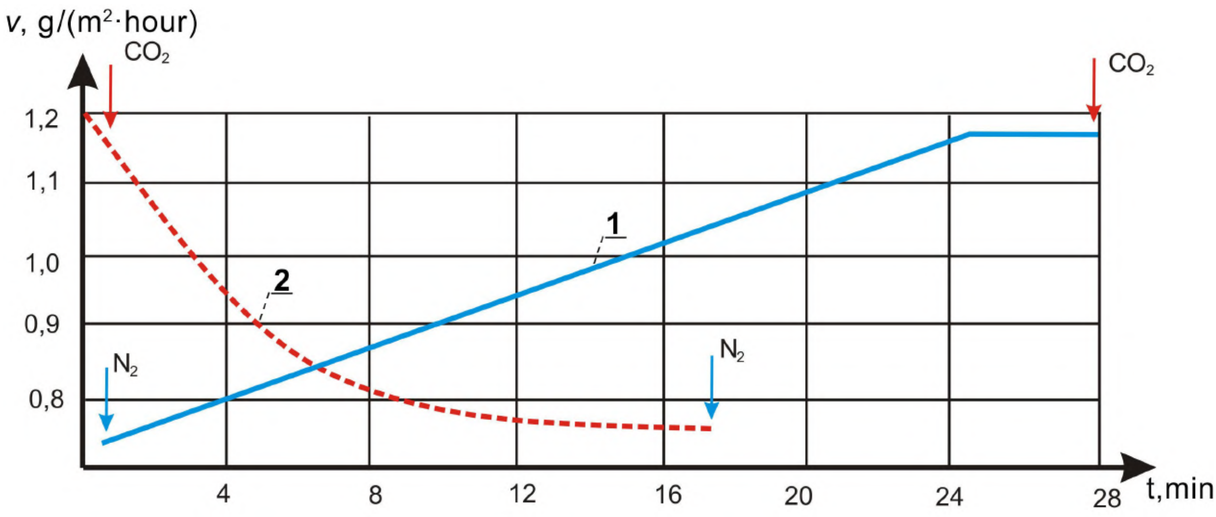

Figure 3. Kinetics of formation of protective carbonate films in a CO_2 atmosphere (1) and their destruction in a N_2 atmosphere (2) at temperature 80°C over solvent 0.5 mol/l CH_3COOH, 0.5 mol/l NaCl.

From the given temperature and kinetic dependencies it follows that acetic acid vapor increases carbon dioxide corrosion. However, the combined action of CO_2 and CH_3COOH causes less corrosion than acetic acid vapor.

According to V. P. Kuznetsov [2], insoluble products of carbon dioxide corrosion located on the metal surface consist of oxide and carbonate compounds of iron.

It can be assumed that with the concentration of water vapor and acetic acid in the well, the destruction of protective oxide films occurs according to the scheme:

$$FeCO_3 + 2\ CH_3COOH \rightarrow Fe(CH_3COO)_2 + H_2O + CO_2;$$
$$FeO + 2\ CH_3COOH \rightarrow Fe(CH_3COO)_2 + H_2O.$$

In an atmosphere of inert nitrogen gas, protective films do not form; corrosion in this case occurs under the electrolyte films by an electrochemical mechanism without the formation of insoluble compounds [2]:

$$Fe + 2\ CH_3COOH \rightarrow Fe(CH_3COO)_2 + H_2.$$

Thus, the influence of carboxylic acids in field wells in the initial period of development is reduced to the destruction of protective carbonate films formed as a result of carbon dioxide corrosion of the metal surface. The highest corrosion rate is at the beginning of droplet water condensation, since the main factors influencing the corrosion rate (acid concentration and temperature) are greatest at this point. The presence of carboxylic acids in condensation water shifts the interval for the beginning of the aqueous fluid condensation in the well towards higher temperatures and depths compared to pure carbon dioxide corrosion.

The intensity of corrosion in the wellbore was determined by the gravimetric method on witness samples installed in the tubing and visually on the tubing raised during repair. At these deposits, there is a correlation between the concentration of iron ions and the concentration of organic acids in the condensation water (table 2).

Table 2. Characteristics of gas condensate wells at the Dnipro-Donetsk basin fields.

Field	**Aggressive components**			**Content of iron ions in water condensate, mg/l**
	$\sum$C organic acids, mg/l	CO_2,% vol.	Cl^{-},g/l	
Opishnianske	100-700	1.0-5.0	up to 70	100-600
Hadiatske	100-700	2.5-3.0	2-35	100-600
Tymofiivske	340-880	1.5	5-25	200-500
Kotelevske	450-700	2.0	up to 130	300-500
Novotroitske	300-700	0.3-0.5	3-50	240-400
Raspashnivske	900-1200	0.1-0.6	0,5-25	300-600
Mashivske	200-900	0.2-0.5	1-25	150-500
Yablunivske	250-500	4-8	0.2-3	300-1000

It has been established that the interaction of organic acids with metal occurs in the Dnipro-Donetsk basin fields in the temperature range of 90-110 °C and at a depth of 3000-3500 m. The interval of action of organic acids on metal tubing depends on the constancy of the regime and the operating time of the well. In constant mode, the effect of organic acids is limited to 100-150 g. The effect of corrosion under the influence of organic acids is especially pronounced in wells where the carbon dioxide content is insignificant $P_{CO_2} < 0.02$MPa (figure 4).

The corrosion rate of ground-based equipment was determined to be 0.002-0.5 g/(m^2·h). It should be noted that the corrosion rate of above-ground equipment is tens of times less than that of underground equipment and 5-15 times less than the calculated rate for carbon dioxide

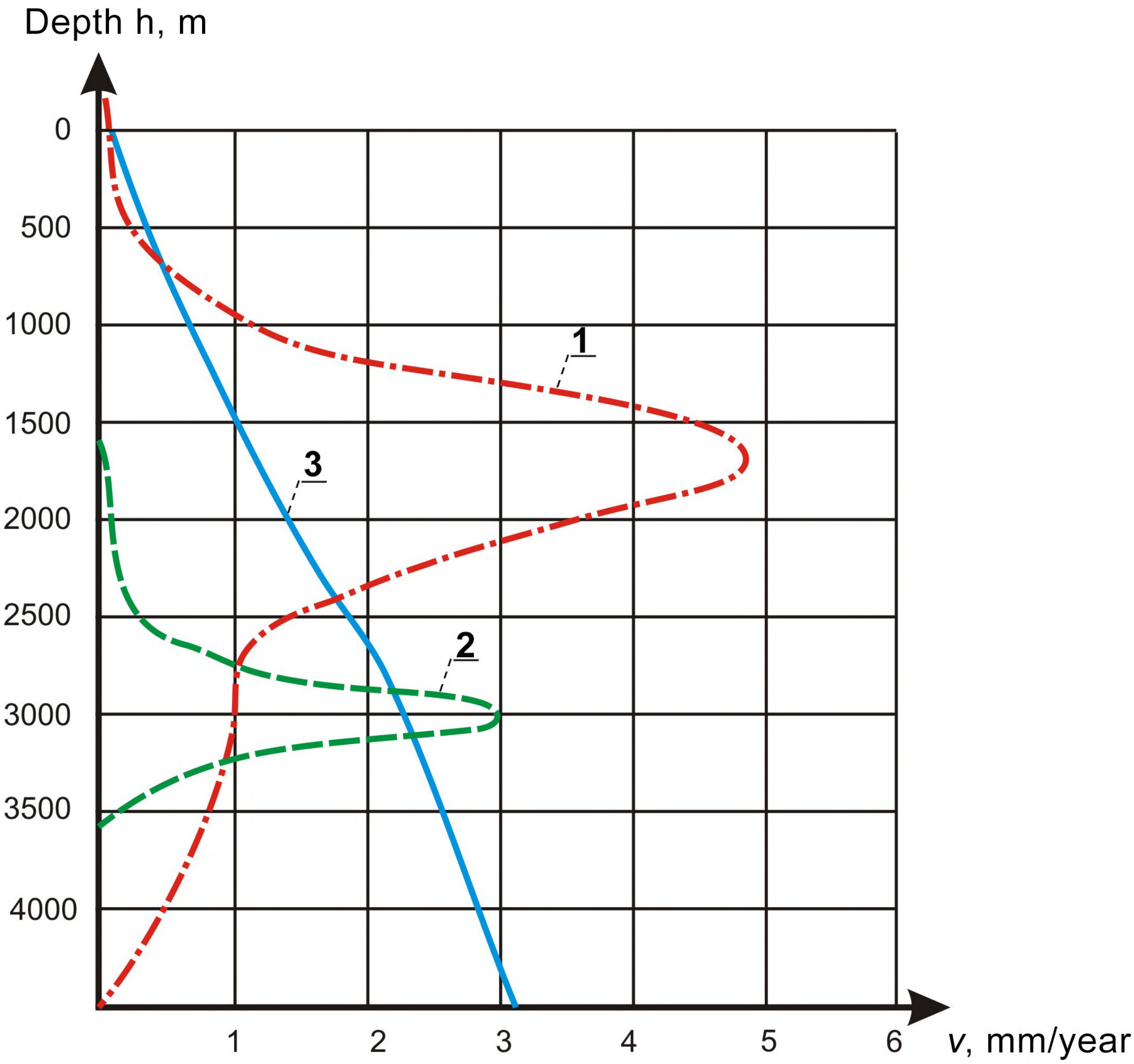

Figure 4. Distribution of corrosion intensity in the wellbore: 1 – corrosion is caused by the general effect of CO_2 and low molecular weight carboxylic acids at the initial stage of field development; 2 – corrosion caused by the action of low molecular weight carboxylic acids at the initial stage of field development; 3 – corrosion caused by the presence of CO_2 and low molecular weight carboxylic acids at the final stage of field development.

corrosion, determined by the V. P. Kuznetsov's equation [2]:

$$lgv = 0.7493 \cdot lgP_{\mathrm{CO}_2} - 0.0095t, \tag{3}$$

where v – corrosion rate; P_{CO_2} – partial pressure of carbon dioxide, Pa; t – temperature, ℃.

The actual rate of corrosion of the surface equipment of the wells of the Yablunivske deposit is 0.3-0.5 g/(m^2·h), while according to equation 1, it is 8-5 g/(m^2·h). The reason for this difference was the inhibitory effect of iron salts of organic acids on carbon dioxide corrosion.

This assumption has been confirmed by laboratory studies. It has been established that the corrosion rate in the medium taken from the well is 0.05-0.2 g/(m^2·h), in the model medium under similar conditions it is 3 g/(m^2·h). After treatment of the selected reservoir water with oxygen to decompose iron salts and remove iron oxides, the aggressiveness of the water condensate increases 10-15 times. For example, the corrosion rate of steel tested under the same conditions in water taken from the mouth of well No. 61 of the Yablunivske deposit, after removal of iron ions, increased to 14 g/(m^2·h).

Thus, iron salts of carboxylic acids – corrosion products during condensation of aqueous fluid in a well, are subsequently inhibitors of carbon dioxide corrosion of gas industry equipment.

5. Conclusion

1. The corrosive effect of organic acids entering the well along with water vapor is to stimulate carbon dioxide corrosion due to the destruction of oxide protective films.
2. In wells with products containing $P_{CO_2} < 0.02$MPa, the equipment corrosion intensity is determined by the concentration of carboxylic acids in the gas, temperature and flow rate. Maximum corrosion damage in wells is in the range of the beginning of carboxylic acid condensation.
3. Iron salts formed as a result of corrosion, during further movement in the wellbore, in plumes, and communications of complex gas treatment plants, are inhibitors of carbon dioxide corrosion.

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Electric drive of coordinated rotation for mechanisms of flow-transport systems

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Electric drive of coordinated rotation for mechanisms of flow-transport systems

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Abstract. The frequency method is currently recognized as the most technically and economically feasible approach for controlling alternating current electric drives. However, systems employing frequency-controlled electromechanical setups with stator circuits, while offering extensive capabilities, present a more intricate challenge for voltage frequency regulation compared to systems utilizing rotor circuits. This complexity arises from the fact that the power of a thyristor frequency converter is comparable to that of electric motors. Consequently, there is a pressing need in contemporary electromechanics for the development of innovative circuit solutions to regulate the performance of flow transport systems. This study aims to design a two-motor electric drive for the mechanisms of flow transport systems with medium to high power, aiming for improved energy efficiency. As a result of this study, it was found that utilizing a cascade circuit in a dual-motor electric drive, along with an additional power source in the rectified rotor current circuit, enables the synchronized rotation of two motors. This synchronization can be achieved not only with identical nominal parameters but also with differing power and synchronous frequency of rotation. The primary advantages of this coordinated rotation approach in a twin-motor electric drive using a cascade scheme include the ability to adjust the power factor of the machines and reduce the power transferred to the control circuit by the thyristor frequency converter, thereby enhancing the reliability of the electric drive's power components. Furthermore, by regulating the rotation frequency of two AC motors, it becomes feasible to enhance overall energy efficiency.

1. Introduction

Presently, energy conservation stands as a primary focus of innovative development in the Republic of Kazakhstan, reflected in the inclusion of energy-saving initiatives in nearly all significant strategic documents [1].

The integration of energy-efficient technologies is evident across six key sectors of innovative and industrial advancement: metallurgy, chemistry, petrochemistry, mechanical engineering, construction materials, and the food industry [2].

Notably, the industrial sector alone accounts for approximately 70% of total electricity consumption, with electric drives of flow-transport systems (FTS) contributing an average of 20% [3].

Flow transport systems in electricity refer to a network of interconnected conveyors or transport mechanisms within industrial settings that facilitate the continuous movement of goods or materials along production lines. These systems are integral to various industries such as manufacturing, mining, and logistics, where the efficient and seamless transfer of materials between different stages of production or processing is essential.

FTS typically consist of a series of conveyors, each designed for specific functions such as loading, transporting, sorting, and unloading. These conveyors may include belt conveyors, roller conveyors, screw conveyors, or pneumatic conveyors, depending on the nature of the materials being transported and the layout of the production facility.

Understanding the operational dynamics of FTS has become increasingly pertinent, given that the interconnected transport and technological lines within enterprises constitute a unified system. Moreover, the contemporary approach of flow production relies heavily on conveyor systems to facilitate the seamless transfer of goods between different stages of production [4]. Belt conveyors play a vital role in this process, maintaining production rhythm, enhancing labor efficiency, and bolstering output. Furthermore, they serve as primary tools for comprehensive mechanization and automation across both primary and ancillary production processes [5].

Typically, the automation system for a network of conveyor lines within an industrial facility must be capable of activating and deactivating different conveyors in a specific sequence, aligning closely with the production process. It ensures the precise speed of cargo transportation and, when needed, synchronizes the speed of various conveyors. Additionally, it manages the blocking of technological and emergency equipment as required [6].

Presently, the majority of FTS utilize adjustable direct current (DC) electric drives to power conveyor actuators [7]. Thyristor converters are employed to control the speed of DC machines within a relatively limited range, typically ranging from 500 to 1900 rpm of the motor shaft [8].

Regarding the electric drive, the FTS can be viewed as a load with static torque unaffected by speed variations. Operating continuously over extended periods, it experiences infrequent starts and stops. There are no stringent demands on the dynamics of the electric drive, and no limitations are placed on the characteristics of transient processes during start-up, braking, or speed transitions [9].

Based on the general attributes, it is evident that the operational demands on the electric drive under normal conditions are relatively modest. However, intermittent instances of sudden load spikes during operation, potentially leading to a substantial increase in static torque, up to the point of actuator jamming, cannot be discounted [10]. Moreover, electric machines operate within an environment laden with dust from construction materials. Hence, in the modernization of such electric drives, the primary focus lies in enhancing their reliability and performance characteristics. In such scenarios, transitioning to asynchronous electric drives with frequency regulation is proposed as a solution. These drives, in terms of functionality and performance, align with the technical requisites and operational conditions of the task at hand [11]. Nonetheless, in making decisions regarding modernization, it is imperative to accurately evaluate the associated costs and, more significantly, compare them with the resultant benefits.

As commonly acknowledged, the frequency method stands out today as the most technically and economically viable control method for alternating current (AC) electric drives [12]. Nevertheless, research indicates that frequency-controlled electromechanical systems utilizing stator circuits, while offering extensive functionalities, pose a technically more intricate challenge for voltage frequency regulation compared to regulation through rotor circuits. This complexity arises from the fact that the power of a thyristor frequency converter (TFC) is comparable to that of electric motors [13].

Consequently, the advancement of novel circuit solutions for regulating the performance of FTS emerges as a pressing task within contemporary electromechanics.

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2. Circuit design for cascade connection of two asynchronous motors

Figure 1 illustrates a functional schematic of a dual-motor electric drive of coordinated rotation featuring a cascade arrangement of two asynchronous motors. In this configuration, the rotor windings of the asynchronous motors are linked in series via a controlled rectifier (CR) within the rotor circuit of the first motor (AM1) and an inverter (I) within the rotor circuit of the second motor (AM2), collectively referred to as a thyristor frequency converter.

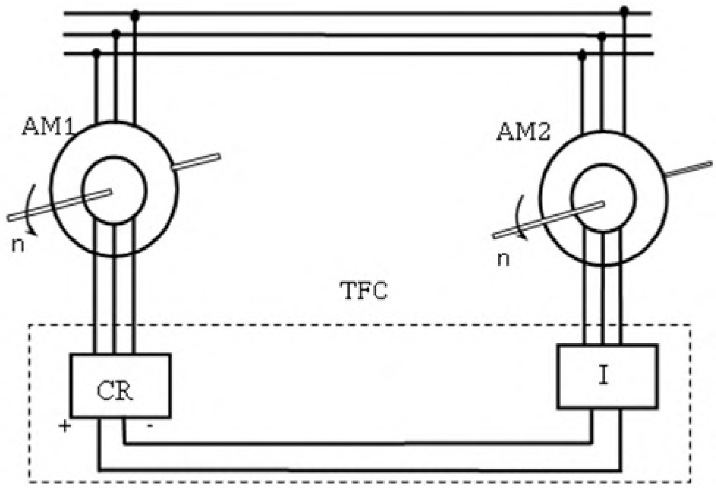

Figure 1. Functional diagram of a double-motor electric drive.

An inherent characteristic of this system is its notable energy efficiency, achieved by harnessing the regenerative energy from the first asynchronous motor to power the thyristor frequency converter within the rotor circuit of the second motor [14].

Consequently, the efficiency of the dual-motor electric drive experiences a substantial boost, particularly as the installed power of the motors increases, further enhancing the system's overall efficiency [15].

For investigating the dynamic characteristics of the coordinated rotation electromechanical system in FTS mechanisms, we conduct computer simulations of a two-motor electric drive setup. This configuration comprises two asynchronous motors with wound rotors, with one motor connected via an asynchronous valve cascade (AVC) circuit and the other connected through a dual-fed machine (DFM) circuit [16, 17].

Figure 2 shows a simulation model of a two-motor electric drive corresponding to the functional diagram shown in figure 1.

3. Results

3.1. Computer simulation results

Computer simulation of a dual-motor electric drive was carried out in the MatLab system. Dynamic characteristics of a two-motor electric drive obtained at various values β (opening angles of the thyristors of the rectifier group) are shown in figure 3 and figure 4.

Examination of the dynamic traits reveals a distinction between the second motor, linked via the dual-power circuit, and the first motor, connected through the valve cascade circuit. Despite identical parameters in the equivalent circuits of both motors, the sliding power directed to the rotor windings of the second asynchronous motor proves inadequate to replicate the characteristics of the first motor [18]. Consequently, an additional power source in the rectified current circuit of the motor rotor is deemed necessary [19].

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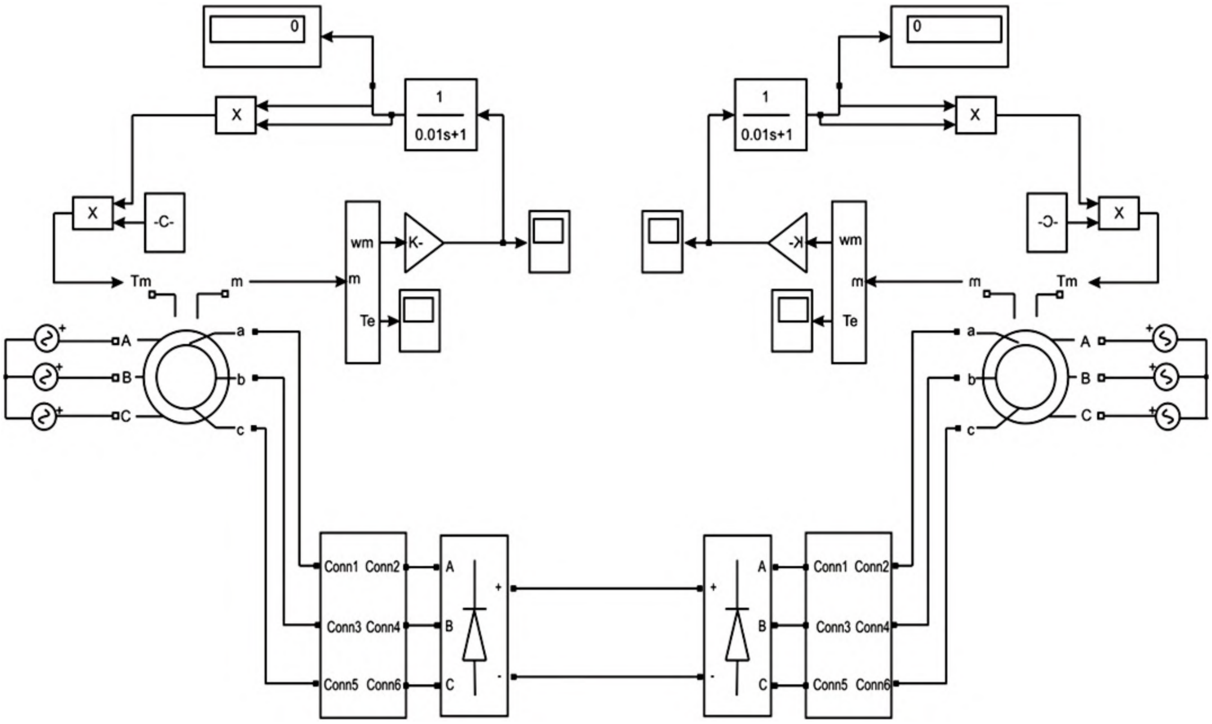

Figure 2. Simulation model of a control circuit for two asynchronous motors in the MatLab environment.

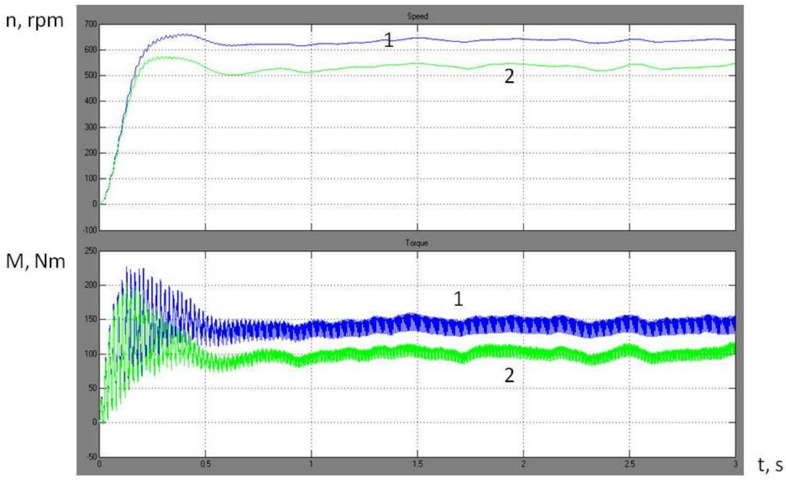

Figure 3. Dynamic characteristics of a two-motor electric drive at $\beta = 30°$: 1 – characteristics of the first motor; 2 – characteristics of the second motor.

3.2. Circuit design with an additional source in the rotor rectified current circuit

A functional diagram of a two-motor electric drive with an additional power source in the rectified current circuit of the rotors of two asynchronous motors is shown in figure 5.

Then, when determining the value of the current in the rotor windings of the second motor, one must proceed from the condition [20]:

$$I_2 = k_i I_{dp} = k_i \left(I_d + I_{ad}\right) \leq I_2, \tag{1}$$

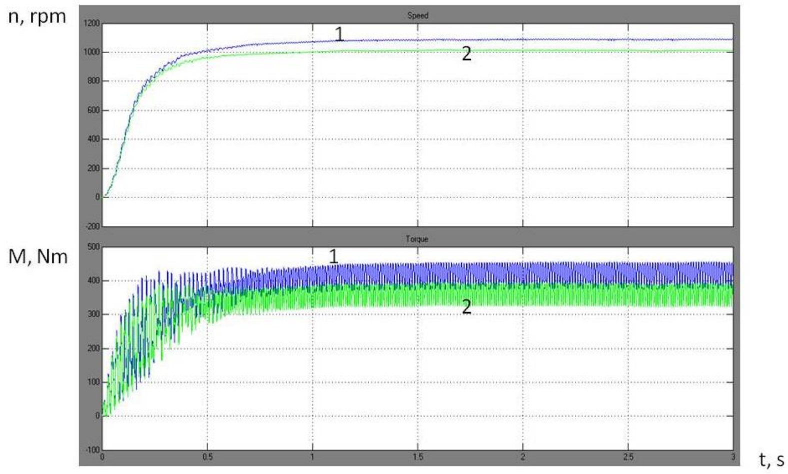

Figure 4. Dynamic characteristics of a two-motor electric drive at $\beta = 60°$: 1 – characteristics of the first motor; 2 – characteristics of the second motor.

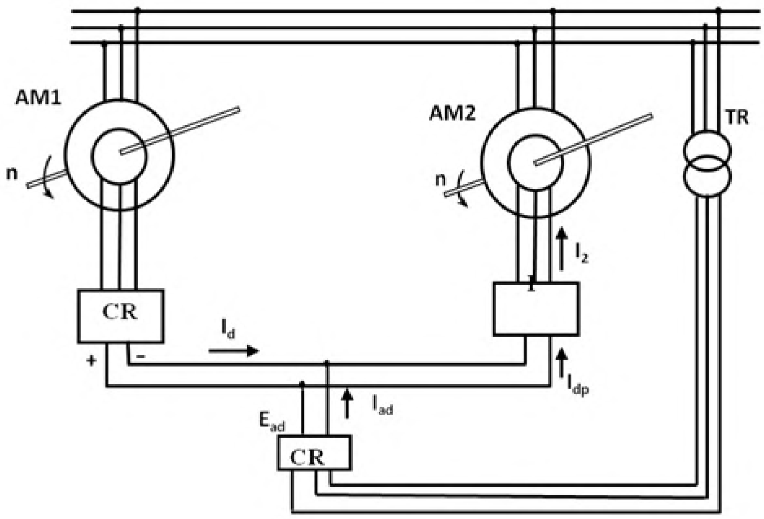

Figure 5. Functional diagram of a double-motor electric drive with an additional power source in the rotor rectified current circuit.

where $I_{dp} = (I_d + I_{ad})$ is rectified current with an additional source, $k_i = 0.815$ is coefficient for current in a three-phase bridge circuit [21].

Additional current [22]:

$$I_{ad} = \frac{E_{ad}}{R_{ad}} = \frac{k_3 U_{tr} cos\alpha}{R_{ad}}, \tag{2}$$

where $R_{ad} = \frac{3x_{p2}s_2}{\pi} + 2r_{p2} + r_{cd}$ is additional resistance [23].

To determine U_{tr} we assume that $cos\alpha = 1$, $cos\beta = 0$, then:

$$I_{ad} = \frac{k_3 U_{tr}}{R_{ad}}. \tag{3}$$

The rated value of the rectified current with an additional power source is determined from

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the condition [24]:

$$I_{dp} = k_i\left(I_{dnom} + I_{ad}\right) \leq I_{2nom}, \tag{4}$$

where I_{2nom} is rated current in the rotor windings of the second motor.

Then:

$$\frac{k_3 U_{tr}}{R_{ad}} + I_{dnom} \leq \frac{I_{2nom}}{k_i}, \tag{5}$$

where $I_{dnom} = I_d$, at $cos\beta = 0$, $s_{1nom} = s_1$, $I_{dnom} = \frac{\pi k_1 E_{p1}}{3x_{p1}} \frac{s_{1nom}-\lambda}{(s_{1nom}(1+k_s q)+\rho)}$ [25].

From here:

$$k_3 U_{tr} = \left(\frac{I_{2nom}}{k_i} - I_{dnom}\right) R_{ad}, \tag{6}$$

where $k_3 = 0.9$ for a three-phase bridge circuit [26, 27].

After conversion:

$$U_{tr} = \frac{R_{ad}}{k_3}\left(\frac{I_{2nom}}{k_i} - I_{dnom}\right). \tag{7}$$

Thus, at low slip values, in order to ensure synchronous rotation of two motors in a cascade circuit, an additional power source must be provided in the rotor rectified current circuit I_{ad}, the output of which changes according to the above law [28].

Figure 6 shows a simulation model of a two-motor electric drive corresponding to the functional diagram shown in figure 5.

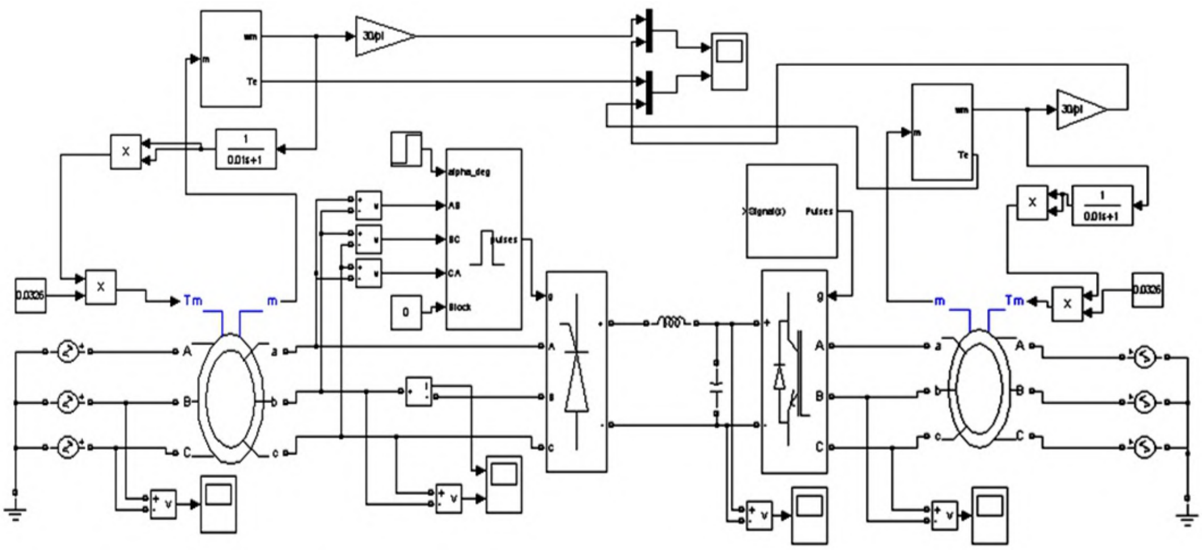

Figure 6. Simulation model of a control circuit for two asynchronous motors in the MatLab environment with an additional power source.

As can be seen from the last figure 7 and figure 8, after connecting an additional power source to the rectified rotor current circuit, the dynamic characteristics of the two motors coincide.

For computer simulation, we utilized the technical specifications of 200 kW motors of type AKN355S6U3 with a rotation frequency of 1000 rpm. The simulation was conducted using MATLAB software, simulating start-up under rated load conditions and assuming even distribution of load on the motor shaft.

To assess the energy-saving and resource-efficient characteristics of the proposed coordinated rotation electric drive scheme, we will compare various systems of double-motor electric drives (DMED) by analyzing technical and economic parameters.

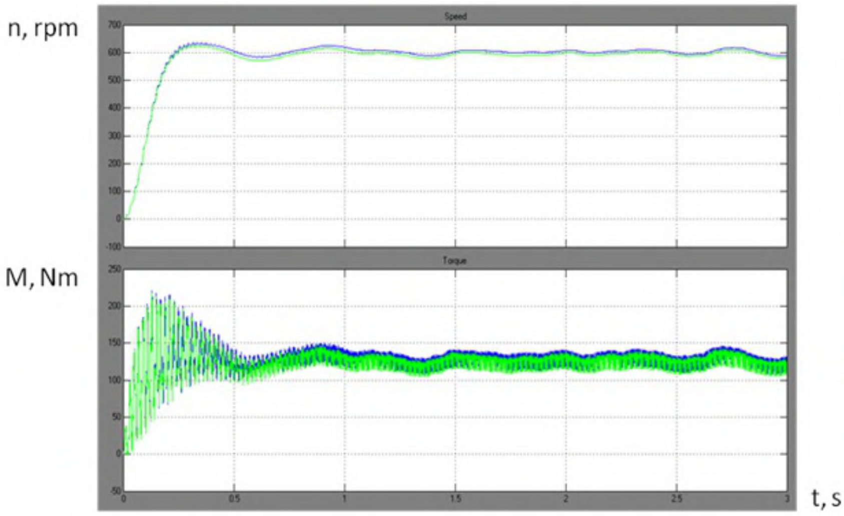

Figure 7. Dynamic characteristics of a two-motor electric drive at $\beta = 30°$.

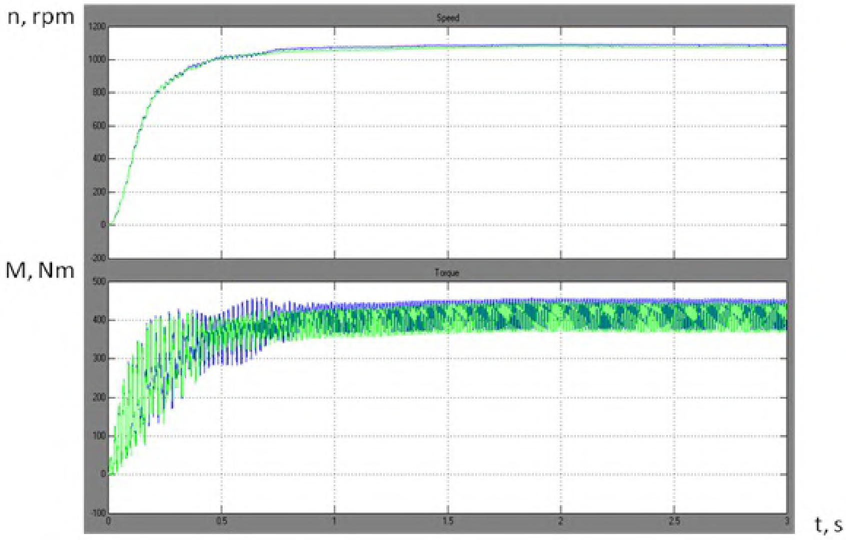

Figure 8. Dynamic characteristics of a two-motor electric drive at $\beta = 60°$.

The installed power of electric motors and power thyristors or TFCs play a significant role in determining the weight, size, and cost of DMED systems. These factors are crucial indicators of DMED performance and largely hinge on the structural diagram of the DMED, the types of TFCs and electrical machines employed, as well as their operational modes. Consequently, these indicators serve as key criteria for comparing different DMED configurations.

As the weight, size, and cost of DMED are primarily influenced by power, rotation frequency, as well as the types of electrical machines and thyristor (or transistor) frequency converters, we derived dependencies of specific cost and mass of these components based on power.

The assessment of cost and weight-size indicators for electrical machines and TFCs relies on specific statistical data concerning commercially available standard sizes of these devices. Analyzing the cost of AC electric machines suggests that evaluating the unit cost as the ratio of the machine's cost to its power is a more practical approach, i.e.

$$C_m = \frac{C_e}{P} = \frac{K_s}{\sqrt[4]{P}}, \tag{8}$$

where C_e is the cost of an electric machine, in conventional units (cu); P is machine power, kW; K_s is specific cost indicator at a given rotation frequency and $f = 50$ Hz. If we take an asynchronous motor with a power of 100 kW as the base machine, then at $n_s = 750$ rpm, $K_s = 60$; at $n_s = 1000$ rpm, $K_s = 48$; at $n_s = 1500$ rpm, $K_s = 35$.

It's important to highlight that the specific cost of an asynchronous motor with a wound rotor is typically 10–12% higher than that of an asynchronous motor with a squirrel-cage rotor, given the same power and speed.

Figure 9 illustrates the relationship between the specific cost of an asynchronous machine with a wound rotor and power at different rotation frequencies. From the graph, it's evident that the specific cost of the machine increases as the synchronous rotation frequency decreases. This indicates that high-speed electric machines are more cost-effective than their low-speed counterparts.

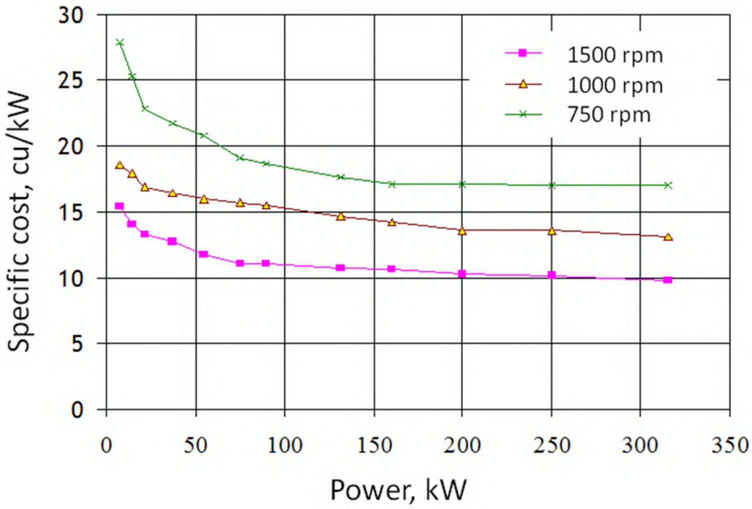

Figure 9. Dependence of the unit cost of an asynchronous machine on power at various rotation frequencies.

A similar dependence would be applicable for TFCs, indicating that

$$C_{TFC} = \frac{C_{TF}}{P_{TFC}} = \frac{K_{TF}}{\sqrt[4]{P_{TFC}}}, \tag{9}$$

where C_{TF} and P_{TFC} are the cost in USD and power in kW TFC; K_{TFC} is specific indicator of TFC power; $K_{TFC} = 510$ and K = 0.333 for a transistor frequency converter.

To conduct a technical and economic evaluation of DMED, we examined the following systems:

1. Frequency-controlled dual-motor electric drive (with TFC situated in the stator circuit of each motor).
2. Double-motor electric drive utilizing a dual-power machine (with TFC positioned in the rotor circuit of each motor).

3. Two-motor electric drive incorporating an asynchronous valve cascade and a dual-power machine (with one TFC situated in the rotor circuit of two motors).

The specific cost of a frequency-controlled DMED, with TFC located in the stator circuit, is determined by the following expression:

$$C_{1DMED} = 2\left(C_{as} + C_{TFC}\right), \tag{10}$$

where C_{as} is the specific cost of one asynchronous motor; C_{TFC} is cost of TFC.

The specific cost of DMED based on dual-fed machines (figure 1), when the TFC is in the circuit of each rotor, is determined by the following expression

$$C_{2DMED} = 2\left(C_{as} + C_{CTFC}\right), \tag{11}$$

where C_{CTFC} is cost of the TFC in the rotor circuit.

The specific cost of DMED based on AVC–DFM, when there is one TFC in the rotor chain of two engines, is determined by the following equality

$$C_{3DMED} = 2C_{as} + C_{CTFC}. \tag{12}$$

It's worth mentioning that the power rating of the TFC in the stator circuit closely matches that of asynchronous motors. Consequently, the variable frequency electric drive system along the stator circuit is more costly compared to the electric drive utilizing the dual-power machine circuit.

The TFC power in the rotor circuit will be equal to

$$P_{TFC} = sP_1, \tag{13}$$

where s is slip, the maximum value of which depends on the control range (for most general industrial motors $s_{max} = 0.3$); P_1 is the power of an asynchronous motor with a wound rotor.

Figure 10 illustrates the relationship between the specific cost of different DDPS systems and the power of the primary engines. It's evident from the graph that this indicator remains relatively constant across a wide power range. The DMED system following the AVC–DFM scheme proves to be more economical compared to DMED systems employing the TFC scheme in both the stator and rotor circuits of each engine. An examination of the weight and size parameters of electric machines can be conducted based on specific static data regarding commercially manufactured motors.

As is known, for an alternating current machine the following equality is true:

$$G_{em} = \frac{G}{P} = \frac{K_g}{\sqrt[4]{P}}, \tag{14}$$

where G is the mass of the electric machine, kg; P is machine power, kW; K_g is specific mass indicator at a given rotational speed and $f = 50$ Hz. If we take an asynchronous machine with a power of 100 kW as the base machine, then at $n_s = 750$ rpm, $K_g = 24$; at $n_s = 1000$ rpm, $K_g = 19.8$; at $n_s = 1500$ rpm, $K_g = 16$.

As demonstrated, a comparative assessment of DMED systems concerning cost, weight, and size indicators reveals that the DMED system following the AVC–DFM scheme is considerably more economical across the entire power spectrum compared to DMED systems adopting the TFC–AM and DFM schemes. Moreover, it does not compromise on weight and size indicators.

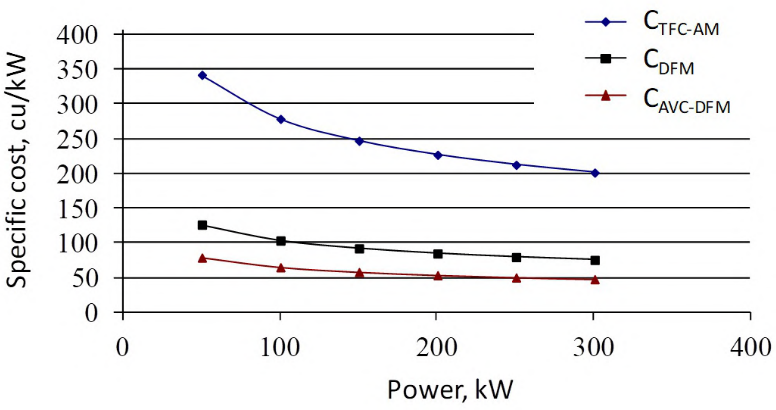

Figure 10. Dependence of the unit cost of an asynchronous machine on power at various rotation frequencies.

4. Conclusions
Therefore, employing a cascade circuit in a dual-motor electric drive, supplemented by an additional power source in the rectified rotor current circuit, enables the synchronized rotation of two motors. This synchronization can be achieved not only with identical nominal parameters but also with differing power and synchronous frequency of rotation.

The primary advantages of this approach to coordinated rotation in a twin-motor electric drive using a cascade scheme include the capacity to adjust the power factor of the machines. Moreover, it reduces the power transferred to the control circuit by the thyristor frequency converter, thus enhancing the reliability of the electric drive's power components. By regulating the rotation frequency of two AC motors, it becomes feasible to enhance energy efficiency [29,30].

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Modelling and forecasting the production potential of renewable energy sources in the context of sustainable development

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Abstract. The Ukrainian energy sector is experiencing a crisis. The necessity for sustainable development in Ukraine's regions, as well as energy independence, stems from the destruction of infrastructure and the consequences of dependency on Russian resources. The current trend is to develop renewable energy sources at the regional level, resulting in a more decentralized model. The article examines the empirical relationship between the causality of production, the potential of renewable energy, and the factors that influence the country's economic growth, such as export, electricity, total final consumption, and total energy supply. The authors propose applying the system approach principle to the study of renewable energy source production in order to ensure the country's energy security, contribute to increasing competitiveness on the international market, and develop a model based on the production of renewable energy sources and waste in Ukraine's difficult economic development conditions. To model the production of renewable energy sources, which is one of the vectors ensuring energy security, the authors used the software product E-Views, which allows for making informed decisions based on statistical analysis and forecasting. During the research process, the authors demonstrated that more effective achievement of sustainable development goals will be facilitated by the formation of a reasonable approach to renewable energy production and the development of a sustainable development policy for Ukraine's regions, which should have significant differences based on the region's specifics.

1. Introduction

The relevance of renewable energy is due to a number of significant factors that affect modern society and the near future. The use of renewable energy helps reduce the negative influence on the environment because, at the moment, the increase in greenhouse gas emissions and other types of pollution causes severe problems such as global warming, rising sea levels, and other bad consequences. Renewable energy provides an opportunity to diversify and decrease our dependency on finite resources, as we observe today that reliance on traditional energy sources, particularly coal and oil, endangers economies and geopolitical stability, potentially leading to war. To prevent wars and other future conflicts over energy supplies, the potential of renewable energy should be chosen, reducing dependence on imported energy carriers.

Additionally, several countries are implementing policies to limit greenhouse gas emissions, with renewable energy serving as an effective tool to achieve these objectives. As a result, renewable energy is acknowledged as a critical component of current sustainable development and resource management strategies, and its importance grows in the face of global environmental and energy issues.

2. Literature review

Renewable energy sources are becoming increasingly significant in the context of the geopolitical crises. The financial market is undergoing a change, with a primary focus on increasing corporate sustainability and its impact on business strategies [1]. This can be explained by the Paris Agreement, which places huge corporations in the forefront of the fight against climate change. Aluchna et al. highlights the role of institutional investors in driving companies to publish social information and corporate transparency in the renewable energy sector [2]. The development of the green economy should begin at the local level, as indicated in the papers by Afroz and Muhibbullah [3], and Dmuchowski et al. [4], because the dynamic linkages between non-renewable and renewable energy sources and economic growth are studied. This nonlinear methodology provides a methodological perspective that may be used to evaluate Ukraine's economic growth potential through the implementation of renewable energy. Ahmad, Zhang and [5], and Saqib et al. [6] conduct a comprehensive review of renewable energy sources (RES) and electricity demand forecasting models, with a focus on smart grid applications and buildings, to ensure the development of technological innovations for environmental sustainability.

According to Stern and Valero, innovation is at the nexus of growth and zero-emissions transition [7]. Understanding forecasting models is critical for strategic planning and policy formation as Ukraine pursues energy security through renewable energy sources. Such an understanding is critical to Ukraine's long-term energy security plan. The role of the government and macroeconomic stability continue to be important considerations in determining strategy and maintaining long-term development. The escalation of environmental issues necessitates the search for an adequate system and resources to address them without compromising economic growth. This demands a shift from resource-based to green economic development [8, 9].

Understanding the policy consequences is crucial for coordinating modeling efforts with national energy security objectives. Countries are creating collaborative energy initiatives and are always looking for sustainable energy alternatives. This may be seen in the post-pandemic cases for EU energy and climate policies, particularly following Russia's invasion of Ukraine. The studies by Miík and Nosko [10], and Barbier [11] examine the impact of geopolitical events on energy policy and ecological revival in democratic countries.

Furthermore, Europe actively refuses to cooperate with Russian energy resources, sparking debate within the community about geopolitical considerations, policy implications, and the challenges faced by EU member states, particularly Hungary, in implementing sanctions against Russian oil [12–15]. Global energy consumption is rising, with policy implications. It is vital to understand the causes contributing to the growth of energy demand and to explore appropriate policy actions to address the issues connected with energy consumption trends. Much of the renewable energy can be generated locally, reducing the requirement for huge energy infrastructure and fuel transportation. This helps to system stability and reduces the risks associated with international energy commerce, particularly in times of geopolitical or economic uncertainty that may limit access to traditional sources.

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3. Materials and methods, starting hypotheses

Various factors influence renewable energy production, development, and potential, including economic, technological, infrastructural, resource, and other considerations. The majority of published studies in the present literature investigate theoretical and empirical correlations. Despite the relationship, there have been very few empirical studies that investigate the relationship between the causality of production and the potential of renewable energy and the factors that determine a country's economic growth, such as E – export, EI – electricity, TC – total final consumption, and TS – total energy supply.

The authors propose applying the system approach principle to the study of renewable energy source production in order to ensure the country's energy security, increase its competitiveness on the international market, and develop a model based on the production of renewable energy sources and waste in Ukraine's difficult economic conditions. This principle is founded on the idea of viewing the system as a whole, with components interacting with one another and the external environment. According to the authors, this method allows us to think of the energy system as an interconnected complex of many aspects, such as renewable energy production and waste management, which will help to ensure energy security. The chosen approach includes system integrity, which is not limited to individual components; component interaction – verification of the cause-and-effect relationship between the selected variables; and an emphasis on system management to achieve goals, such as optimizing energy production, efficient resource use, waste minimization, and ensuring sustainable development. A systems approach to modeling renewable energy and waste management enables a more thorough and integrated knowledge of energy-ecological systems, as well as the development of effective solutions for resource sustainability.

We are using the E-Views application to model renewable energy production, which is one of the vectors for assuring energy security. The multivariate regression model appears like this:

$$Y = f(X_1, \ldots, X_n) \tag{1}$$

We examine the influence of the selected most significant variables and the density of their link using the model we have developed. The E-Views application is used because it allows for the creation of an econometric model, forecasting, and drawing conclusions to assure the country's energy security. As a result, the selection of the specified software product is relevant in terms of instrumental capabilities to the tasks addressed in this study. The statistical data used in the analysis were collected between 2010 and 2021, hence the model has 12 observations. The equation below describes the model's general appearance:

$$P = f(TC, E, TS) \tag{2}$$

where P – Production (PJ); TC – Total final consumption (PJ); E – Exports (PJ); TS – Total energy supply (PJ); PJ is petajoules.

When selecting the most significant factors, we apply the reliability principle, which adequately reflects the current state of renewable energy production, the information availability principle, which involves the use of official World Energy Balances Highlights 2023 data [16], and the representative principle, which states that each variable chosen for the sample is the most significant and justified.

4. Results and discussion

4.1. Renewable energy as a vector for the country's energy security and sustainable energy future

Renewable energy is a crucial component of ensuring energy security. The use of renewable energy sources allows the country to diversify its energy mix. Instead of relying on scarce resources such as coal or natural gas, which a country may lack or have in limited supply, solar, wind, hydropower, and other renewable sources can be employed. This decreases the risk of energy crises and helps to provide a more sustainable energy supply. In addition, renewable energy is a key strategic method to ensuring the sustainability and security of the country's energy system. The benefits of diversifying energy sources include:

- reduction of energy risks associated with possible fluctuations in the cost of raw materials, changes in the world markets of energy resources, political and economic turbulence;
- reducing dependence on energy imports, in particular oil, gas, and coal, which collectively reduces vulnerability to economic or political changes in exporting countries;
- support for sustainable development, which contributes to achieving environmental goals and reducing the negative impact on the environment;
- ensuring the stability and reliability of the energy system thanks to renewable energy through the placement of various sources. The diversity of renewable sources allows to ensure the stability of the energy system in case of emergency situations, such as natural disasters or geopolitical conflicts, and reduces the risk of interruptions in the supply of energy;
- the possibility of using the latest innovative technologies, as well as solar panels, wind turbines, hydropower, biomass, etc. The launch and development of renewable technologies stimulates the domestic market, promotes the attraction of investments in the energy sector and the development of the innovative sector. This can lead to the creation of new jobs, support for small and medium-sized enterprises and increase the country's competitiveness in the global energy market. This enables countries to choose technologies that best suit their conditions and needs.

In general, renewable energy is not only a source of clean energy, but also a strategic component in enhancing the country's energy security and establishing a secure, sustainable energy future.

4.2. Econometric modeling of renewable energy production, hypothesis testing, correlation analysis and causality analysis

Globalization has put the world's economies in a new economic context that is linked to the growth of renewable energy sources. However, how specifically and forcefully do the factors influence the output of renewable energy sources as a vector of Ukraine's energy security? The answer to this issue can be reached by examining the functional relationship between renewable energy production and the variables being researched. For this purpose, the authors utilized the software product E-Views, which enables the generation of results in the form of tables, graphs, and charts. Among the econometric methods available in E-Views, we employed Descriptive Statistics, Hypothesis Testing, Correlation and Covariance Analysis, Regression Analysis, Forecasting, and Pairwise Granger Causality test.

To identify the relationship between the production of renewable energy sources and the selected variables, we will use the multivariate regression method. The general form of the regression equation is as follows:

$$P = C(1) \times TC + C(2) \times E + C(3) \times TS + \epsilon \tag{3}$$

where $C(1, 2, \ldots, n)$ – the regression coefficients for the selected variables, ϵ – the vector of random deviations.

The correlation matrix built by the authors allows establishing the relationship between the selected variables (table 1).

Table 1. Correlation matrix of selected variables.

	P	TC	E	TS
P	1	0.9570	-0.5629	0.9859
TC	0.9570	1	-0.6380	0.9157
E	-0.5629	-0.6380	1	-0.4229
TS	0.9859	0.9157	-0.4229	1

The relationship between the selected factors is positive and strong for P and TC is 95.7%, for positive P and TC is 98.6%, and the inverse relationship between P and E is 56.3%. The positive relationship between the production of renewable energy sources and the total final energy consumption and supply indicates their close interdependence.

It should be noted that the inverse relationship between renewable energy production and exports can benefit the country not only economically through market opportunities, but also in terms of sustainable development, job creation, and environmental impact reduction. Countries that actively develop and produce renewable technology might gain a competitive advantage in the global market and export their innovations. This might involve exporting solar panels, wind turbines, energy storage technologies, and other components of green systems. As a result, the inverse relationship between the selected factors can reveal new challenges and opportunities for the energy industry, helping to transition to a more sustainable and efficient energy future.

The cause-and-effect relationship between the selected variables (TC, E, TS) and P – the production of renewable sources is investigated using the Granger causality test. The idea behind the test is whether past values of one variable can be used to predict another. Granger causality test results are interpreted based on F-statistics and p-value ("Prob." in table 2). If the p-value is less than the specified level of significance (usually 0.05), then the null hypothesis is rejected, which indicates the existence of a causal relationship between the variables. If two coefficients are simultaneously statistically significant, then the relationship is two-way or inverse. The presence of a two-way relationship may indicate the existence of a third variable that is the real cause of changes in the two variables represented in the equation. The tests were carried out for lags 2 and 3. The test results are presented in table 2. The null hypothesis of the test claims that there is no causal relationship.

The pairwise Granger Causality test was run on all variables with lags 2 and 3, allowing the

Table 2. Pairwise Granger Causality test on all the variables, 2010-2021.

Null hypothesis	Lags: 2			Lags: 3	
	F-Statistic	Prob.	Conclusion	F-Statistic	Prob.
TC does not Granger Cause P	1.97484	0.2333	accept	1.39093	0.4442
P does not Granger Cause TC	0.28717	0.7620	accept	1.48818	0.4261
E does not Granger Cause P	1.22682	0.3686	accept	0.91554	0.5598
P does not Granger Cause E	0.09167	0.9139	accept	1.28900	0.4649
TS does not Granger Cause P	1.33825	0.3424	accept	1.09300	0.5105
P does not Granger Cause TS	1.84250	0.2515	accept	1.64915	0.3991
E does not Granger Cause TC	5.89534	0.0484	reject	21.6483	0.0445
TC does not Granger Cause E	0.00578	0.9942	accept	2.19041	0.3287
TS does not Granger Cause TC	2.15782	0.2111	accept	1.72181	0.3879
TC does not Granger Cause TS	1.64984	0.2817	accept	0.89424	0.5664
TS does not Granger Cause E	0.11878	0.8904	accept	1.27114	0.4687
E does not Granger Cause TS	2.30734	0.1950	accept	1.29792	0.4630

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study to incorporate the long-term interaction of all indicators chosen for examination. The table displays this information. Two data points suggest that there is a causal relationship between the selected variables. Note that the test revealed that "E does not Granger Cause TC", which means: the historical values of the E – export variable cannot be used as an effective prognostic indicator for changes in the TC – total final consumption variable, i.e., exports have no effect on and do not determine the total final consumption of renewable energy in the country, whereas exports determine renewable energy production volumes. As a result, the historical correlations between these two variables may not be obvious enough to foresee.

The pairwise Granger Causality test demonstrated that all selected variables can be used to model and anticipate P – production from renewable sources.

Table 3 shows the results of additional regression analysis, allowing us to examine the impact of chosen variables on renewable energy generation in Ukraine over the twelve-year period 2010-2021.

Table 3. The results of multi-factor regression of P (least squares method, sample 2010–2021, 12 observations).

Variable	Coefficient	Std. Error	t-Statistic	Prob.ăă
TC	0.279402	0.087251	3.202280	0.0126
E	-0.886836	0.096788	-9.162705	0.0000
TS	0.841676	0.030692	27.42310	0.0000
C	6.036263	1.753334	3.442734	0.0088
R-squared	0.999156	Mean dependent var		168.9167
Adjusted R-squared	0.998840	S.D. dependent var		50.22035
S.E. of regression	1.710733	Akaike info criterion		4.172922
Sum squared resid	23.41285	Schwarz criterion		4.334558
Log likelihood	-21.03753	Hannan-Quinn criter.		4.113079
F-statistic	3157.184	Durbin-Watson statistic		2.056079
Prob(F-statistic)	0.000000			

We define the model's requirements for the qualitative parameters of the factors, using a marginal 5% level of significance. Table 3 shows the following results:

- The export variable's coefficient has a negative impact on renewable energy production, whereas the total final consumption and energy reserve coefficients have a favorable impact.
- The value of the regression R^2 indicates how strongly the specified variables are related to renewable energy generation. According to regression calculations, 99% of the increase in P depends on the selected variables (correlation coefficient is 0.99). This indicates the presence of a sufficiently strong connection. The probability of accepting the null hypothesis is close to zero (F-statistic=0.00), which confirms the alternative hypothesis, which indicates the significance of the equation as a whole. The selected variables are significant in terms of impact on P: total final consumption – 1.26%; export – 0.00%; the total energy reserve is 0.00%, and this meets the threshold of less than 5%. As a rule, there are no strict requirements for the constant, but in our case, it is also statistically significant, because it is less than 1%, that is, all indicators are statistically significant. We use the Durbin-Watson (DW) test to determine whether the equation has first-order autocorrelations. The DW criteria has a value ranging from 0 to 4; zones are separated into zones with no autocorrelation, zones with positive and negative autocorrelation, and zones of uncertainty (critical zones). Table 3 shows that the criterion (DW) is 2.056. We use Durbin-Watson statistics to calculate the significant (critical) points d_l and d_u. For the number of observations of 12 and 4 variables at the level of significance α=5%,

0.658<DW<1.864; at the level of significance $\alpha 1 = \%$, 0.449<DW<1.373. This means that there is no autocorrelation of the residuals and we have no reason to reject H_0, that is, we take it as a basis.

- We also use the Breusch-Godfrey test (table 4) to determine the presence of higher (second) order autocorrelation. Second-order autocorrelation testing is equivalent to testing the null hypothesis: it determines whether there is dependency in the model's residual terms at different remote time steps. The Breusch-Godfrey test aims to discover autocorrelation in the regression model's residual terms. That is, we check again to see if the null hypothesis is accepted or rejected. Prob. $F(2,6) = 25.7\%$, and Prob. $\chi^2(2) = 11.24\%$, beyond the 5-10% threshold of significance. This test demonstrates the absence of higher (second) order autocorrelation and the feasibility of accepting H_0.
- The analysis of the information criteria used in the development of this model revealed that Akaike (AIC) = 4.17 and Schwarz (BIC) = 4.11 are small, acceptable values for the model.

Table 4. Breusch-Godfrey serial correlation LM of P (Presample missing value lagged residuals set to zero).

F-statistic	1.718835	Prob. $F(2,6)$		0.2570
Obs*R-squared	4.370999	Prob. $\chi^2(2)$		0.1124
Variable	Coefficient	Std. Error	t-Statistic	Prob.ăă
TC	0.010647	0.081900	0.129999	0.9008
E	0.016398	0.089712	0.182784	0.8610
TS	-0.001757	0.029171	-0.060238	0.9539
C	-0.061819	1.630922	-0.037904	0.9710
RESID(-1)	-0.043678	0.338559	-0.129012	0.9016
RESID(-2)	-0.655309	0.353852	-1.851930	0.1135
R-squared	0.364250	Mean dependent var		$1.51 \cdot 10^{-14}$
Adjusted R-squared	-0.165542	S.D. dependent var		1.458918
S.E. of regression	1.575052	Akaike info criterion		4.053306
Sum squared resid	14.88472	Schwarz criterion		4.295759
Log likelihood	-18.31984	Hannan-Quinn criterion		3.963541
F-statistic	0.687534	Durbin-Watson statistic		2.619865
Prob(F-statistic)	0.651059			

The next step is to evaluate the autocorrelation of the model's remaining members (table 5). A residual term correlogram is used to investigate the structure of residual terms and uncover potential patterns or connections among them.

The "prob" value reflects the probability that the chosen statistical model has a null hypothesis of no residual autocorrelation. If "prob" is less than a predetermined significance level (such as 0.05), the null hypothesis is rejected, indicating a statistically significant autocorrelation. All "prob" values in the created model are greater than the significance threshold, implying that the model can continue in its current form without further analysis to account for the identified autocorrelation in the remaining terms.

4.3. Testing the model for the presence of heteroscedasticity and the quality of the selected variables in the model and forecasting

The next step is to test the model for heteroscedasticity, which allows us to evaluate whether the remaining members of the model have uneven dispersion, i.e., whether the error variance changes

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Table 5. Correlogram of residuals.

	ACă	PAC	Q-Stat	Prob
1	-0.028	-0.028	0.0120	0.913
2	-0.554	-0.555	5.1677	0.075
3	-0.235	-0.398	6.2012	0.102
4	0.219	-0.296	7.2040	0.125
5	0.206	-0.295	8.2250	0.144
6	0.008	-0.208	8.2267	0.222
7	-0.171	-0.317	9.2124	0.238
8	0.088	0.029	9.5397	0.299
9	-0.031	-0.204	9.5952	0.384
10	-0.001	0.050	9.5952	0.477
11	-0.000	0.008	9.5952	0.567

Table 6. The results of heteroskedasticity test of P.

Test: White	Obs*R-squared	5.25508	Prob. Chi-Square(9)	0.7670
Test: Breusch-Pagan-Godfrey	Obs*R-squared	3.377655	Prob. Chi-Square(3)	0.3370
Test: Harvey	Obs*R-squared	2.705518	Prob. Chi-Square(3)	0.4393
Test: Glejser	Obs*R-squared	2.253159	Prob. Chi-Square(3)	0.5216
Test: ARCH	Obs*R-squared	2.575876	Prob. Chi-Square(1)	0.1085

in relation to the independent variable values. Heteroskedasticity can impair the efficiency and consistency of model parameter estimates. We do this check using tests (table 6).

If the p-value obtained from the test is less than a specified significance level (for example, 0.05), then there is statistically significant evidence of heteroskedasticity and the null hypothesis is rejected. Analysis of table 5 showed that the p-value in all tests is greater than 5%, so it is possible to accept H_0.

The next step is to evaluate the model for explanatory power, which indicates how well the model represents the variation in the dependent variable (the variable the model is trying to explain) based on the input independent variables. This is an important aspect of evaluating the effectiveness of the model and its ability to adequately describe the data (table 7).

Next, we compared P to variables (with a focus on regressors), which implied a partial analysis of the relationship between P and other variables while accounting for the influence of regressors or independent variables. In this instance, "partial" refers to the analysis that takes into consideration the effects of the given regressors, effectively eliminating their influence to investigate the net link between renewable energy output and the remaining variables (figure 1).

This analysis shows how P evolves as the effects of regressors are taken into account. Figure 1 depicts a partial correlation that measures the strength and direction of the relationship between two variables $P - TC, P - E$, and density. A strong relationship is observed for $P - TS$, while taking into account the influence of other regressors, and allows to isolate the net effect between P and other variables, regardless of the influence of regressors.

Figure 2 depicts the normality test for the residuals. Figure 2 demonstrated the normality of the model's residual distribution, with a Kurtosis value of 2.51, which is more than zero and suggests a strongly peaked distribution; this indicator indicates that the distribution is near normal. However, 2.51 does not indicate a deviation from normality on its own, but it may be one indicator to consider in conjunction with other statistical features and graphs when assessing the normality of the residual distribution.

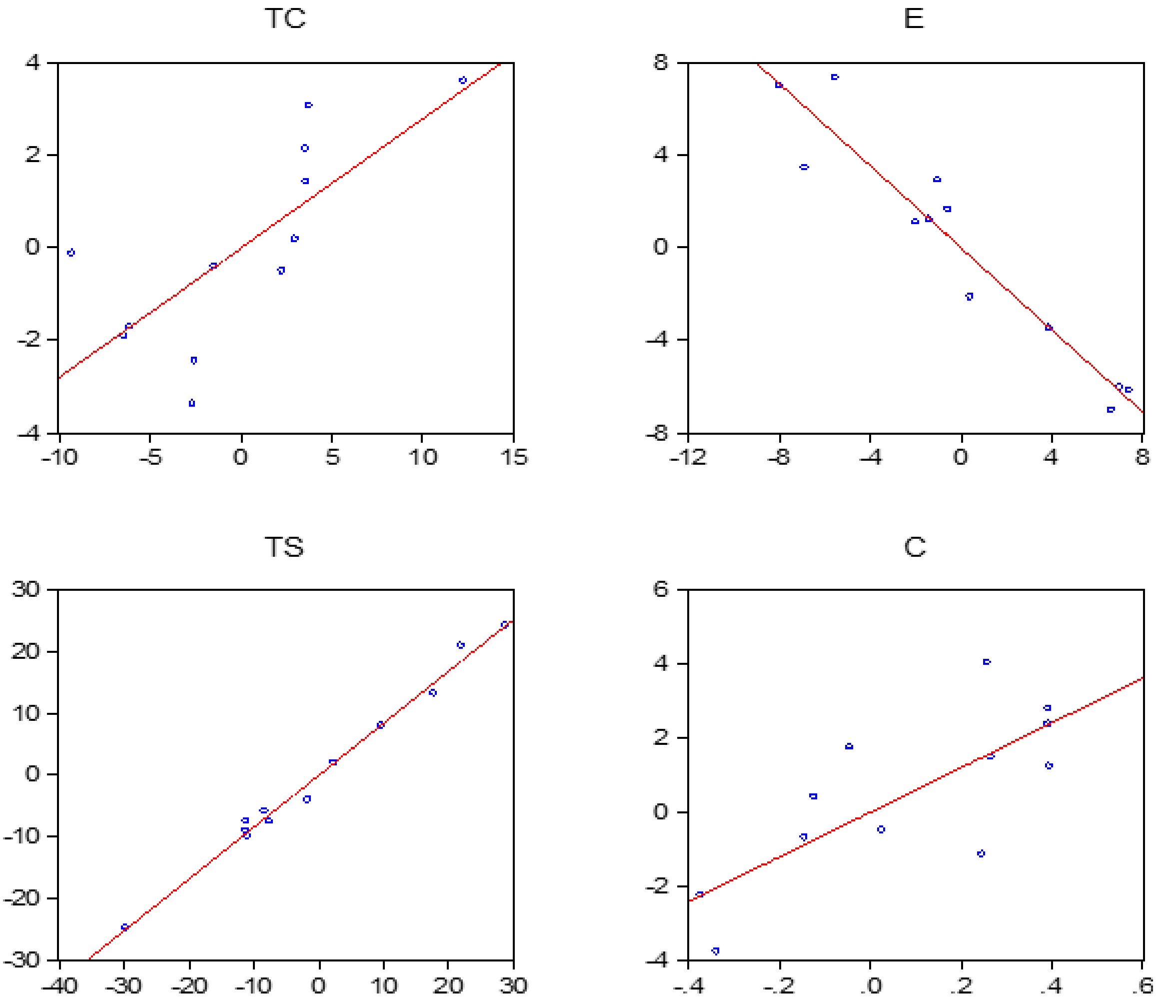

Figure 1. Production vs variables (partialled on regressors).

Table 7. Explanatory ability of the model.

obs	Actual	Fitted	Residual
2010	117	116.9901	0.0098
2011	114	113.5748	0.4251
2012	113	114.1370	-1.1370
2013	146	143.5267	2.4732
2014	137	137.1059	-0.1059
2015	134	136.6305	-2.6305
2016	173	173.6434	-0.6434
2017	188	185.9822	2.0177
2018	202	200.8461	1.1538
2019	200	199.8168	0.1831
2020	246	247.7437	-1.7437
2021	257	257.0021	-0.00217

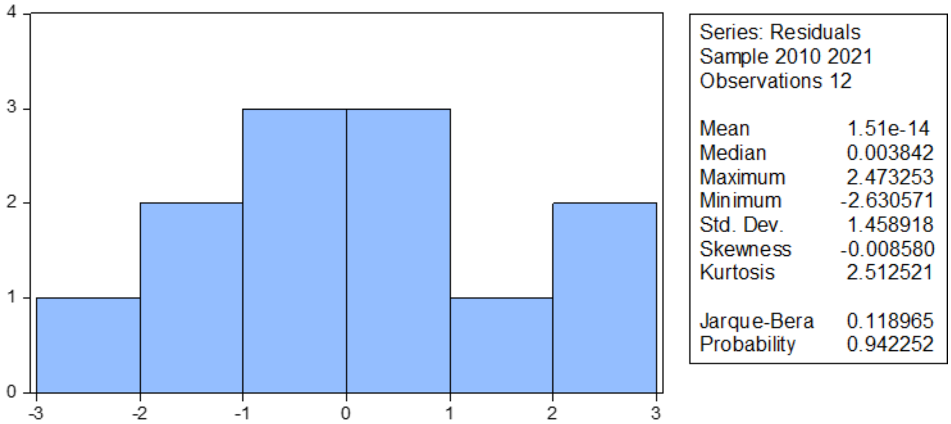

Figure 2. Normality test in $f(P)$.

The skewness indicator value of -0.0085 is a measure of the asymmetry of the value distribution in our model, indicating that it is skewed to the left (negative) and symmetric (skewness is close to zero). That is, skewness shows that the residual distribution deviates slightly from symmetry, close to zero, and does not pose any significant concerns in terms of residual distribution normality.

Figure 2 shows the probability of acceptance of H_0 at a high level and it is 94.2%.

Figure 3 shows the forecasting trend, which has a positive growing trend demonstrating the relevance and value of renewable energy production.

In our model, MAPE = 0.66, indicating that the average percentage error between predicted and actual values is 0.66% This means that, on average, predictions differ by 0.66% from actual values. The lower the value, the better, because MAPE implies great forecast accuracy.

So, we have a statistically significant equation with a high coefficient of determination:

$$P = 0.2794 \times TC - 0.8868 \times E + 6.0362 \tag{4}$$

The multiple regression model predicting the development of renewable energy output based on independent factors was successfully tested. All examinations and testing have confirmed the

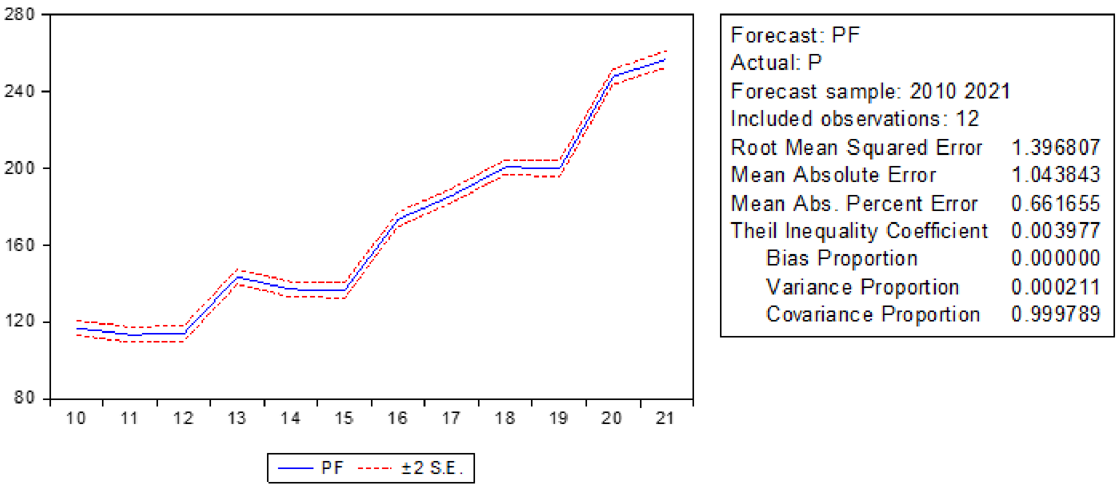

Figure 3. Forecast of P.

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accuracy of this model for Ukraine. This means that:

- the equation is statistically significant with a high coefficient of determination;
- the equation represents an economic-mathematical model at a high level of quality;
- the model built by the authors is adequate and fully acceptable for forecasting in the future with a deviation of 0.66% from the actual values.

5. Discussion

Further discussion of the selected problem is important for the future of all countries throughout the world. The authors revealed this issue by utilizing Ukraine as an example, taking into account the country's unique economic development and political environment. Certainly, while dealing with the situation, alternative econometric models might be utilized for predicting. Furthermore, our attention was focused on three variables: total final consumption, exports, and total energy supply; however, the impact of other factors, particularly those affecting renewable energy production, such as climatic conditions, technological innovations, economic factors, and regulation, should be investigated in the future.

It would be useful to evaluate the economic aspects of renewable energy generation, such as the cost of installing and maintaining equipment, efficiency in comparison to conventional energy sources, and the growth of countries' energy markets. These components can be used to broaden and deepen the conversation, encompassing various areas of renewable energy modeling and forecasting for energy security.

The author's multi-regression model of the dependence of renewable energy production growth was constructed and analyzed based on statistical data spanning from 2010 to 2021. However, starting in 2022, the full-scale invasion of Russia into Ukraine began. Therefore, it will be pertinent to examine the repercussions of the war for Ukraine's energy security, as well as the potential impact on the implementation of renewable energy initiatives in future research.

6. Conclusions

The authors conducted study on renewable energy sources as one of the energy security vectors of Ukraine, modeling and projecting their production. They identified:

- the presence in the long-term period of factors that affect the total volume of production of renewable sources, which is one of the vectors/directions of ensuring energy security, the formation of a balanced and sustainable energy system of Ukraine in conditions of sustainable development;
- the existence of a strong relationship between the amount of renewable energy production and the total final consumption and the total energy reserve, and the correlation coefficients are quite high;
- the analysis of the coefficients in equation (4) showed that an increase in the value of the TC variable by 1% should lead to a positive contribution to the production of renewable energy by 0.3%; if the value of TS increases by 1%, then the value of P will increase by 0.8%; if the value of variable E increases by 1%, it will lead to a negative contribution to P by 0.9%;
- the modeling and forecasting of renewable energy generation demonstrated a good trend in the context of modern energy security difficulties and a general increase in awareness of environmental pollution problems. This trend, based on Ukraine's experience, demonstrates the active deployment and development of modern renewable energy technology. Increased output of renewable energy sources, including solar, wind, and hydropower, is a significant positive element. This contributes to the diversification of the country's energy mix, reduces dependence on traditional sources, and contributes to the creation of a sustainable and

environmentally friendly energy sector. An additional factor of the positive trend today and for the future is the active participation of Ukraine in the implementation of international programs and agreements aimed at supporting renewable energy. This will allow the country to receive technical and financial support for the modernization and development of renewable energy, especially after the end of the war (because statistical data were analyzed before the start of the full-scale Russian invasion of Ukraine). The overall favorable trend in Ukraine's renewable energy production helps to reduce dangerous substance emissions and encourages sustainable energy development. Supporting and developing this trend is crucial for Ukraine's energy security, including achieving energy independence and addressing environmental concerns in the modern world;

- to more effectively achieve the goals of sustainable development, countries, including Ukraine, should encourage the formation of a reasonable approach to the production of renewable energy sources as well as the development of sustainable development policies for Ukraine's regions, which should differ significantly based on regional characteristics. The current geopolitical scenario, as well as the war in Ukraine, have demonstrated the implications and problems confronting European countries and Ukraine, demonstrating the benefits of renewable energy sources in maintaining Ukraine's energy security.

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Determination of operating parameters of accumulative electric heating systems

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Abstract. The article presents the results of research aimed at determining the parameters and characteristics of storage heating systems, justifying the possibility of using heat accumulators to increase the efficient use of energy that is generated, including from renewable sources. The virtuality, frequency and significant dependence on natural conditions and climate of renewable energy sources, as well as the need to optimize their installed capacity, leads to the need to use energy storage installations. The presence of efficient energy batteries is a prerequisite for modern efficient energy and heat supply systems. The methodology of the work is based on our own theoretical and experimental studies, which provide practical recommendations for the arrangement of energy accumulators obtained using renewable heat sources. This is especially relevant for Ukraine during the period of active military operations on its territory, the destruction of traditional energy sources and a shortage of generating capacity. Recommendations have been developed for the design of heat accumulators for heating systems of residential and public buildings. Their effectiveness has been assessed under conditions of limited use of fossil fuels and the use of hybrid energy sources. Scientific and practical results of the work make it possible to carry out low-cost reconstruction of heating systems for the introduction of storage systems using electrical energy, the source of which is wind and solar energy. Such developments are becoming particularly relevant in Ukraine, taking into account the requirements for ensuring the stability and efficiency of infrastructure facilities in war conditions.

1. Introduction

Thermal batteries are one of the important elements when addressing the issue of replacing fossil fuels, such as natural gas, with renewable energy sources, as well as when using low-potential energy sources. The use of energy batteries when installing hybrid systems is also mandatory [1]. Accumulation makes it possible to solve important tasks set in the updated energy efficiency directive [2].

The use of thermal accumulators in thermal power systems with renewable sources, including the generation of electrical energy from biogas, helps reduce CO_2 emissions into the atmosphere and reduce the greenhouse effect [3].

Renewable energy sources generate energy that is variable in both time and quantity. For example, the use of solar or wind energy for heating purposes is practically impossible without the use of heat storage. In addition, heat accumulation can be considered as a means of leveling the energy consumption schedule. When using two and three-rate tariffs, heat accumulators make it possible to obtain a significant economic effect associated with the possibility of obtaining energy during periods of the lowest tariffs.

An additional challenge is charging for the installed power of the power generator. The use of heat accumulators makes it possible to reduce the installed capacity of consumer heat and power systems by leveling the load and covering peak loads using accumulated heat. In addition, heat accumulation allows for more efficient use of renewable energy sources with variable generation capacity.

There are two types of such batteries. The first type includes those whose temperature increases as a result of the supply of heat, the second – those in which the supplied heat is spent on some kind of phase transition – most often melting. In the first case, the specific energy of the battery is determined by the heat capacity of the storage substance and the permissible change in its temperature, and in the second – by the latent heat of phase transition.

The article discusses the issues of determining the operating parameters of water batteries without a phase transition.

The developed methodology for determining the characteristics of thermal accumulators can be applied not only when using electrical energy, but also for any other energy sources in heating systems. It is also possible to use the technique when using hybrid energy sources.

Algorithm for researching the given problem:

- work with literary sources on the topic of using electrical energy in heating systems [4–6];
- analysis of the issue of using heat accumulators in electric heating systems [7–9];
- full-scale studies of operating modes of heating systems in residential and public buildings;
- construction of a mathematical model to determine the operating parameters of heat accumulators;
- determination of the main parameters of the heat accumulation system;
- experimental verification of the obtained dependencies to determine the operating parameters of the accumulation system.

2. Methodology

The design and installation of storage heat supply is facilitated by the continuous increase in the price of natural gas and other types of fossil fuels. This, in turn, leads to an increase in tariffs for thermal energy received in centralized and other heat supply systems.

Thus, renewable energy can be considered as a useful alternative to energy obtained by burning fossil fuels (such as natural gas).

However, the use of electrical energy for heating needs helps solve the problems of power engineers themselves. Namely, the problem of a shortage of shunting capacity to regulate the daily load schedule of the energy system against the backdrop of a surplus of electrical energy generation. The use of electrical energy for heating buildings at night can be a good way to level out the unevenness of electrical energy consumption in the power supply system. Especially when using electrical energy generators using renewable and alternative energy sources. And also in conditions of military threats to infrastructure facilities.

The advantage of using electrical energy as an energy carrier is also the ability to maintain the temperature regime of heating water in boilers with high accuracy.

The use of electric heating systems makes the task of assessing the efficiency of storage systems extremely relevant. From a thermodynamic point of view, from 1 m^3 of natural gas of group L or E according to the classification [10,11] with a calorific value of up to 40 MJ/m^3 it is theoretically possible to obtain (provided that the process is 100% efficient) up to 11 $kW{\cdot}hour/m^3$ of electrical energy.

However, the low efficiency of condensing thermal power plants leads to the fact that the amount of generated electrical energy does not exceed 3-4 kW·hour/m^3, which immediately affects electricity tariffs.

Let's perform a thermodynamic analysis of the use of various types of energy.

The advantage of electric heating boilers, without a doubt, is their high thermal efficiency of converting electrical energy into heat, which is close to 99%.

For comparison, when using the best hydrocarbon fuel – natural gas – in non-condensing boilers, the thermal efficiency does not exceed only 91-92%. It cannot be large due to the fear of condensation of water in the composition of fuel combustion products. In condensing heat generators, the efficiency of fuel use can be increased to 95-96% [12].

However, the difference in the efficiency of heating gas and electric boilers for municipal energy is easily compensated by the extremely low efficiency of the steam power cycle for generating electrical energy at condensing power plants.

The situation may change if renewable sources are used to generate electricity. However, the potential of such energy sources in the cold season, as a rule, decreases, and the virtuality of obtaining energy from renewable sources, on the one hand, and the high requirements for the reliability of heating systems, on the other, transform this task into a multi-variant one. This conclusion may also be valid when comparing the cost of energy, unless the cost of electrical energy is subject to any preferences, such as a "night tariff".

A significant reduction in the cost of electrical energy occurs when switching to a two-part (or three-rate) tariff for electrical energy. This method of payment for electrical energy makes it possible to implement such a method of electric heating as electric storage heating.

During the night period of the day, during the period of preferential tariff for electrical energy, the electric storage system takes electrical energy from the network for the purpose of heating water and accumulates hot water in the storage tank. The volume of accumulation must be sufficient for full operation of the heating system during the daytime period, when the selection of electrical energy from the network at an increased tariff is impractical. During this period of the day, coolant will be withdrawn from the storage tank.

A schematic diagram of the arrangement of such a system is shown in figure 1.

It is possible to determine the main parameters of such a system and performance indicators of its operation.

Initial data for calculation:

M_o – the flow rate of water that circulates in the heating system of the building is determined according to the relationship:

$$M_o = \frac{Q_o}{(t_1 - t_2)c_w}, \tag{1}$$

where Q_o is the heat flow for heating the building, depends on the heat-protective characteristics of the building envelope, kW; c_w – heat capacity of water, kJ/(kg·°C);

M_b – the mass of water in the accumulation tank (kg) which can be written as:

$$M_b = V_b \rho_w, \tag{2}$$

where V_b is the volume of the accumulation tank, m^3; ρ_w – density of water in the container, kg/m^3.

Let us introduce other factors that influence the solution of the problem.

N is the power of the electric heater, which should ensure heating of water with a flow rate of M_o to a temperature t_1 sufficient to ensure comfortable conditions for people to stay in the building during periods of both supply and accumulation, and consumption of thermal energy.

τ_n – duration of night supply of electrical energy and accumulation of heat throughout the day, at a reduced tariff, per hour, for example $\tau_n = 7$ hours (from 23:00 to 6:00) – time of supply and accumulation of energy.

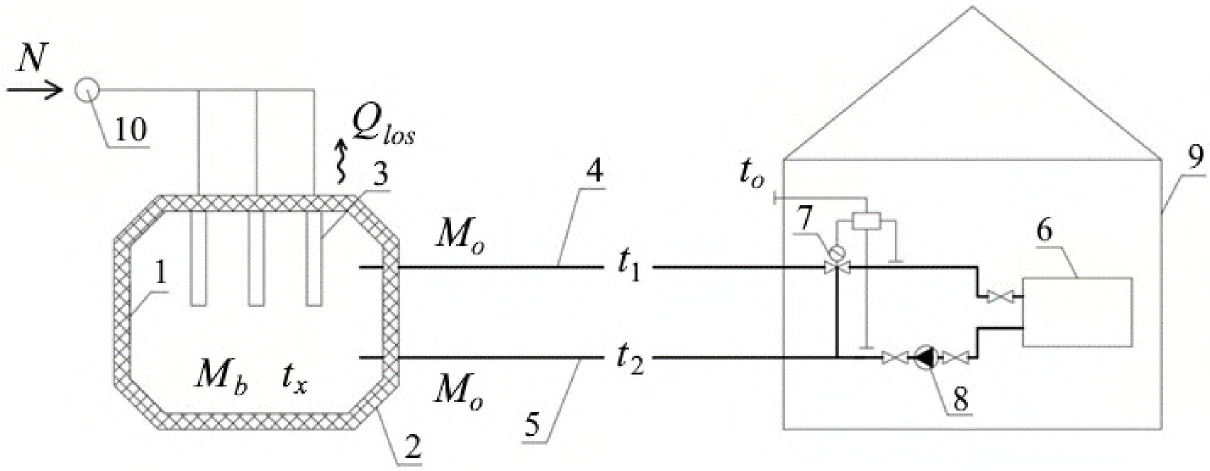

Figure 1. Schematic diagram of the arrangement of an electric storage system with a water storage tank: 1 – water storage tank; 2 – thermal insulation of the tank; 3 – electric heater; 4 – hot water supply pipeline with coolant temperature t_1; 5 – return pipeline with temperature t_2; 6 – heating devices for building heating systems; 7 – three-way control valve; 8 – circulation pump; 9 – heated building; 10 – multi-tariff electric meter; Q_{los} – heat loss from the electric storage tank.

$\tau_u = (24 - \tau_n)$ – daily duration of energy use without external replenishment. During this period of the day, the use of electrical energy to heat the coolant is not economically justified, since the daily tariff for electrical energy exceeds the night tariff.

η_l is a coefficient that takes into account heat loss from the battery tank to the environment. Provided effective thermal insulation of the tank $\eta_l = 0.93 \div 0.95$ (heat loss to the environment is $5 \div 7\%$).

$n' = Q'_o/Q_o$ is a coefficient that takes into account the presence in the system of buildings and structures for which it is possible to partially or completely reduce the amount of heat released for heating during the period of energy supply and accumulation (for example, due to the accumulation of heat in building envelopes or a temporary decrease in temperature in the room).

$n'' = Q''_o/Q_o$ is a coefficient that takes into account the share of buildings in which it is impossible to temporarily reduce the supply of heat for heating during the period of energy accumulation.

Q'_o is a heat flow for heating that part of buildings in which it is possible to reduce the amount of heat supplied for heating during the period of energy supply and accumulation, kW.

Q''_o is the heat flow for heating that part of the buildings in which it is not possible to reduce the amount of heat released for heating during the accumulation period, kW.

Thus, the total amount of heat (kW·hour) supplied for heating needs for a group of buildings and structures can be written as an equation:

$$Q = Q_o \cdot n' \cdot (24 - \tau_n) + Q_o \cdot n'' \cdot 24. \tag{3}$$

If the coefficient $n' = 0$, then this means that there are no buildings in which a temporary reduction in heat supply at night at the subsidized tariff is possible. If during the night period there is a possibility of disconnecting all buildings from the heat source, then $n' = 1$, and the coefficient $n'' = 0$. If it is possible to reduce the heat consumption for heating at night by half, the values of the above coefficients will have the values $n' = 0.5$ and $n'' = 0.5$.

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3. Results and discussion

The main design parameters of electric storage heating systems include the following:

- required electric power of the heater – N;
- capacity of the hot water storage tank – V_b.

Such a tank, under conditions of periodic supply of energy to water, must provide the required temperature of the coolant in the supply line of the heating system throughout the entire period of energy use. This temperature, in addition, depends on the temperature of the external air and is determined in accordance with the temperature schedule for the release of the coolant.

We determine the required power of the electric heater from the system heat balance equation:

$$\eta_l \cdot N \cdot \tau_n = Q_o \cdot n' \cdot (24 - \tau_n) + Q_o \cdot n'' \cdot 24. \tag{4}$$

After some mathematical transformations we get:

$$\eta_l \cdot N \cdot \tau_n = Q_o \cdot (24 \cdot n' - \tau_n \cdot n' + 24 \cdot n''). \tag{5}$$

Or the required electrical power of the heater should be:

$$N = \frac{Q_o \cdot (n' \cdot (24 - \tau_n) + 24 \cdot n'')}{\eta_l \cdot \tau_n}. \tag{6}$$

The results of calculations of the required thermal power of the electric heater of the system depending on the outdoor temperature, up to which the accumulation mode of operation will be ensured, are shown in figures 2, 3 and 4.

In order to make the calculation results universal and possible for use in the conditions of any building with an arbitrary value of Q_o, the ordinate axis of the graph shows not the absolute, but the relative value of the required power of the electric heater k, which is defined as the ratio of the absolute power N to the calculated value of heat consumption for heating.

$$k = \frac{N}{Q_o}. \tag{7}$$

This coefficient shows how many times the power of the electric heater must exceed the calculated heat flow for heating in order for the heat accumulation system to operate with comfortable microclimate parameters.

For example, in accordance with figure 2, to ensure the functionality of an electric storage heating system for buildings with complete heat extraction ($n' = 0$) during the energy storage period, the required power of the electric heater must exceed the calculated heat requirement for heating by 4 times.

Calculations were made for operating conditions over the entire range of outside air temperatures. For example, provided that the storage system operates at a temperature not lower than -10°C (87% of the time of the total duration of the heating period), an electric heater power at the level $N = (2.5 \div 2.6) Q_o$.

Provided that the duration of the energy supply and accumulation cycle increases from seven to ten hours, the power of the electric heater can be reduced to $N = (1.8 \div 1.9) Q_o$.

However, in this case, the economic attractiveness of the system is significantly reduced. In addition, the question of how to provide consumers with heat for heating during the period when the external air temperature reaches values from -10°C to a standard value of -23°C becomes relevant. And this is about 600 hours of work for the climatic conditions of the city with a standard outdoor temperature about $t_o = -23$°C.

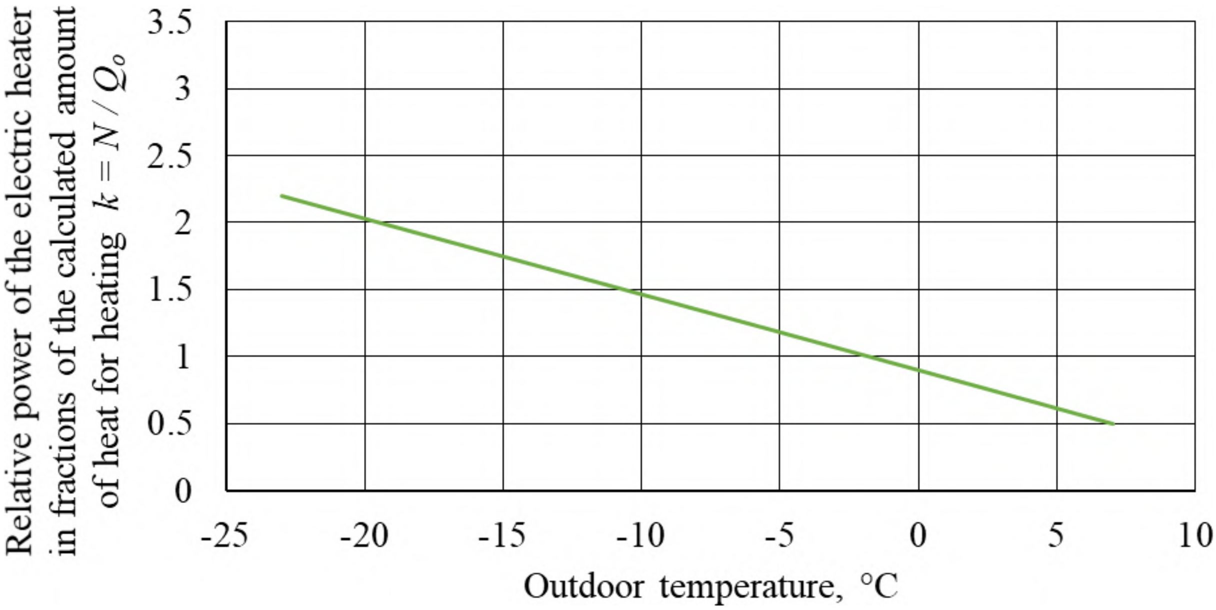

Figure 2. Dependence of the required power of electric heaters of an electric storage heating system on the outside air temperature, up to which the system can operate in storage mode without additional heat supply. $n' = 1, n'' = 0$ (during the night charging period, all buildings do not consume thermal energy for heating).

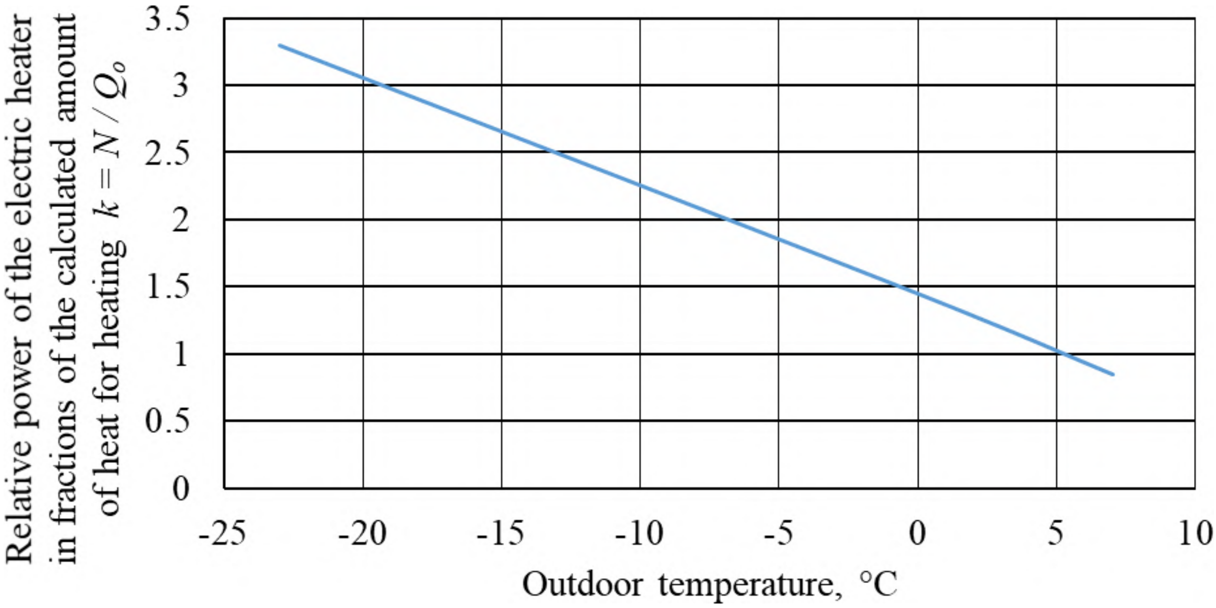

Figure 3. Dependence of the required power of electric heaters of an electric storage heating system on the outside air temperature, up to which the system can operate in storage mode without additional heat supply. $n' = 0, n'' = 1$ (during the night charging period, all buildings consume thermal energy for heating in full, depending on the outside temperature).

In the absence of a heat source using fossil fuels, the only alternative to supplying heat during this period is the selection of electrical power during the daytime period at an increased tariff, which is economically unprofitable.

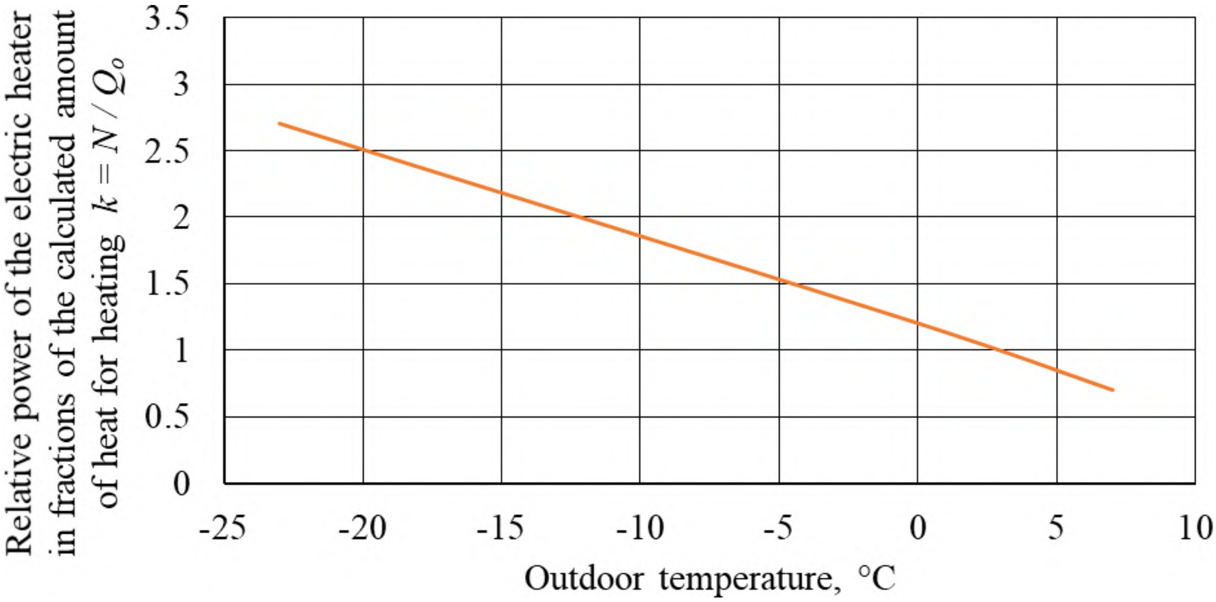

Figure 4. Dependence of the required power of electric heaters of an electric storage heating system on the outside air temperature, up to which the system can operate in storage mode without additional heat supply. $n' = 0.5, n'' = 0.5$ (at night, 50% of buildings do not consume thermal energy for heating, and the remaining 50% consume energy in full, depending on the outside temperature.

Thus, reducing the consumption of primary fuel (for example natural gas), which is usually the main goal of using electric storage heating systems, will lead to an increase in the cost of heating buildings. For hybrid heat supply systems that use several energy sources, including renewable types of energy, the choice of power of the heating source determines the feasibility, cost-effectiveness and possibility of switching from one energy source to another.

A significant problem with the use of electric storage heating systems is the need to modernize external electrical networks, due to the inability of electrical networks to withstand the additional loads that arise during electric heating. Thus, when introducing an accumulative electric heating system in an 80-apartment residential building with an estimated heat requirement for heating of 250 kW, the power of the electric heater, in accordance with the graph in figure 2, should be about 900 kW. Connecting such a heater to the existing electrical networks of the house seems problematic.

Another important design parameter of the system is the volume of the water storage tank.

The capacity of such a tank must ensure the required temperature of the coolant throughout the entire period of its circulation in the system without replenishing energy during the period of increased tariff.

Let us denote by t_x the current values of the coolant temperature in the tank. And through n – the relative capacity of the tank, which we will express through the calculated value of the hourly water consumption in the heating system, M_o':

$$n = \frac{M_b}{M_o'}, \tag{8}$$

where M_o' (t/hour) is the estimated flow rate of network water in the heating system, determined in accordance with the relationship:

$$M_o' = \frac{Q_0}{\Delta t \cdot c_w} \cdot 3.6, \tag{9}$$

where Q_o the heat flow for heating buildings, kW; $\Delta t = t_1 - t_2$ – calculated temperature difference in the heating system (for example $\Delta t = 90 - 70 = 20$°C); $c_w = 4.2$ kJ/(kg·°C) – heat capacity of water.

Let us write the heat balance equation for the period of water withdrawal from the tank in the form:

$$c_w \cdot M_b \cdot t_1 - c_w \cdot M_o' \cdot t_1 + c_w \cdot M_o' \cdot t_2 = c_w \cdot M_b \cdot t_x. \tag{10}$$

From (10) we obtain the value of the current temperature of hot water during its selection from the tank – t_x:

$$t_x = \frac{M_b \cdot t_1 - M_o' \cdot (t_1 - t_2)}{M_b} = \frac{k \cdot M_o' \cdot t_1 - M_o' \cdot (t_1 - t_2)}{k \cdot M_o'} = \frac{t_1 \cdot (n-1) + t_2}{n}. \tag{11}$$

In accordance with the calculations on dependence (11), after the end of the first cycle of the coolant circulation, provided that $M_b = 10M_o'$ the water temperature in the tank will decrease from the initial 95°C to 93°C. If the volume of the tank is lied to $M_b = 5M_o'$, then the water temperature after the first circle of circulation will be set at a level of 91°C with a further continuous decrease in temperature in the tank during the subsequent circulation.

Thus, it is possible to create a graph of the dependence of the necessary capacity of the tank-accumulator on the temperature of the outdoor air, provided that the installed schedule

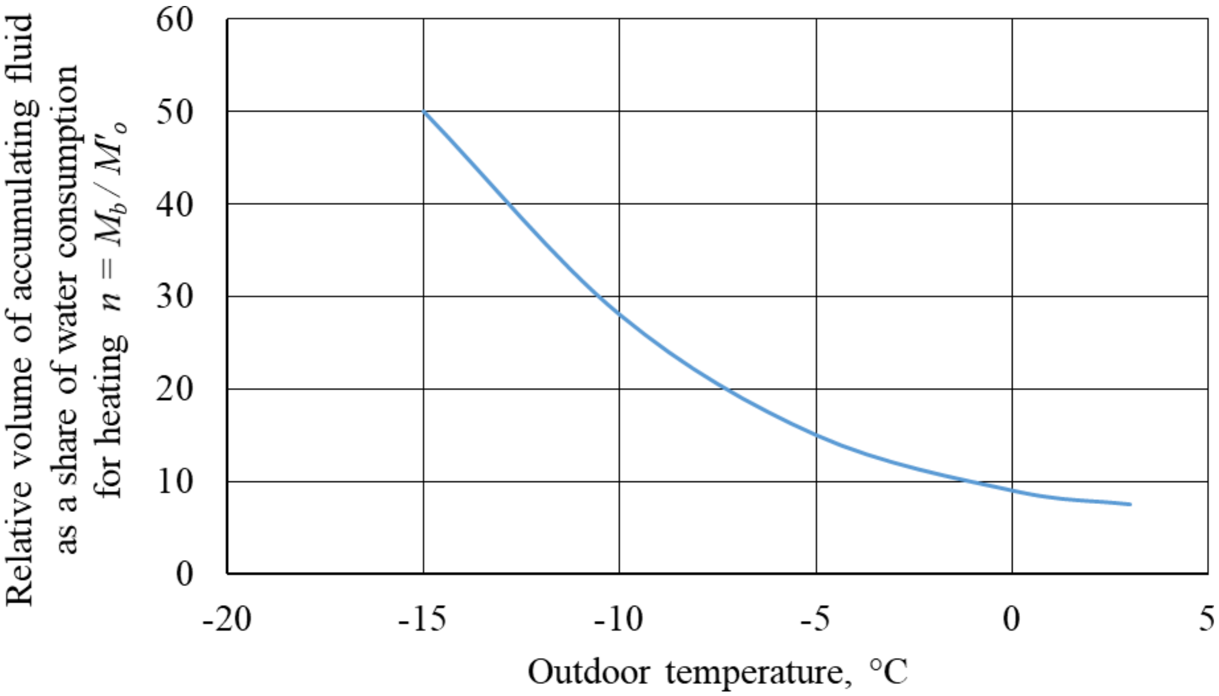

Figure 5. Dependence of the relative capacity of the accumulator tank “n” of the electric storage system on the outside air temperature, to which it is possible to operate the heating system to ensure comfortable microclimate parameters without additional consumption of electrical energy in the heating system during the daytime hours at an increased tariff.

of heat flow and maintain the optimal microclimate parameters in the premises. The condition for constructing the graph is also that continuous selection of the coolant from the tank is made without replenishment of energy from the outside in the daytime period of the day for an increased tariff for electric energy.

Figure 5 shows such a graph, which was obtained during the experimental stage of the research. It is built for a calculated temperature difference in the supply and return lines of the heating system $\Delta t = 20°\text{C}$.

The studies were carried out for an accumulation heating system of a residential building with a calculated heat consumption for heating of 250 kW without replenishing energy up to an outside air temperature of -10°C. The required capacity of the accumulation tank in accordance with the obtained schedule was no less than $V_b = 25V_b'$ or 134 m^3. Figure 6 shows a photo of such a tank for an accumulation heating system.

Placing a tank of this size in a building caused understandable problems. Therefore, it was placed outside and was carefully insulated. The heat supply system provided heat to the building of a sanatorium in the city of Mirgorod, Poltava region (Ukraine). A significant reduction in the size of the storage tank is possible by performing thermal modernization of the building and reducing the need for heat for heating. So, for example, for the estimated heating requirement of a building of about 40 kW, the volume of the tank is reduced to 34 m^3.

To reduce the building's need for heat, it is necessary to carry out a set of works on thermal

Figure 6. Storage capacity for a heating system with an estimated heat demand (thermal power) of 250 kW.

modernization of the building – increase the thermal resistance of external fences from 1 m^2g/W to 5 m^2g/W, use energy-efficient translucent fences, introduce a ventilation system with heat recovery, install an automated individual weather control system in the building heating point.

Experimental studies on the arrangement of a heating system with water storage tanks confirmed the obtained research results. However, it is noted that placing accumulation tanks of significant size in the premises of a building will require some structural work and significant costs.

4. Conclusions

The paper presents a methodology for determining the main design parameters of an electric storage heating system with water storage tanks.

Dependencies were obtained to determine the required volume of storage tanks and the required power of electric heaters of the electric storage heating system depending on the outside air temperature.

The results of calculations based on the given methodology indicate the possibilities of using electric storage heating systems and give an idea of the limitations that occur when implementing such systems.

As a result of the studies performed, it was shown that the tank capacity and the power of the system's electric heaters depend on the magnitude of the building's heating needs. In this regard, one of the conditions for the successful implementation of electric storage heating systems is the thermal modernization of buildings to a level that meets modern requirements for thermal protection of buildings. Carrying out work on thermal modernization of heat supply facilities and reducing the need for heat for heating significantly increases the efficiency of electric storage systems.

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Study of double short circuits on earth in 10 kV power grids with isolated neutral and with high level penetration RES

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Study of double short circuits on earth in 10 kV power grids with isolated neutral and with high level penetration RES

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Abstract. Proposed study described positive influence of high level penetration of renewable energy sources in distributed electrical networks for power system in total in war conditions. Faults in transmission power lines are analysed and shown depend on level voltage. The paper presents the results of studies of double earth faults in 10 kV networks with an isolated neutral in the MATLAB program package.

1. Introduction

Reliability indicators of power supply systems as a whole are largely determined by the level of reliability of distribution electrical networks voltage of 6-35 kV. In previous work was indicated problem of 0.4 kV power grids [1]. According to various literary sources, the emergency in networks voltage of 6-35 kV, operating in the mode with an isolated or resonance-grounded neutral, is largely connected with the shorting of the phases of the lines between themselves and to the ground [2].

The analysis of damage and experience of operation of 6-35 kV networks [3–5] allow us to made the following conclusions:

- finding and eliminating places with weakened insulation is a complex process, as it requires multiple disconnections of the same network elements;
- a significant share of damage in networks is damage to support and through insulators and switching devices [6, 7];
- specific damage of switching devices from internal overvoltages is quite high and only 3 times lower than from lightning overvoltages [8].

In three-phase electrical networks with an input switch and lines fed from 10 kV substation busbars, during different single-phase short-circuits on two lines, there are cases of non-selective operation of the input switch protection, in the event that the current of the input switch exceeds the tripping set point of the current protection that acts on this switch. At the same time, such an excess occurs before the conditions for tripping of current protections are met, which act to disconnect the circuit breakers connected to the buses and the input circuit breaker. Therefore, the serviceable line will be turned off by the input switch.

2. Importance of distributed sources of generation in times of war

RES were implemented in distributed power grids last few years. Also, the green energy market is developing rapidly because more and more people understand and want to pass on our world to their descendants in at least as good a condition as we received from our parents and distributed power plant can be more safety, then nuclear power plants or condensing heating plants. Other reasons, that see from global surveys that equipment used in green energy is becoming cheaper and more affordable every year. More windmills and solar panels appearing on our streets and in our homes, because energy communities is developing. But it is imported to note that at the current level of development, green generation alone will not be able to meet the full demand for electricity. A lot of RES and distributed power grids were damaged under war attacks also (figure 1 and figure 2).

Figure 1. Damaged photo-voltaic power station.

In blog materials of Yurii Kasich for Energy Club was noted, that small sources of energy are able to provide electricity to settlements close to them, the enemy will of course be able to damage them, but in most cases thermal power plants, hydroelectric power plants, distribution substations are under attack. The lower the voltage class of power lines or substations, the greater their number and the less known to the aggressor. It is there, in those networks, that the distributed small generation of Ukraine (solar power plants, wind power plants, bio-fuel

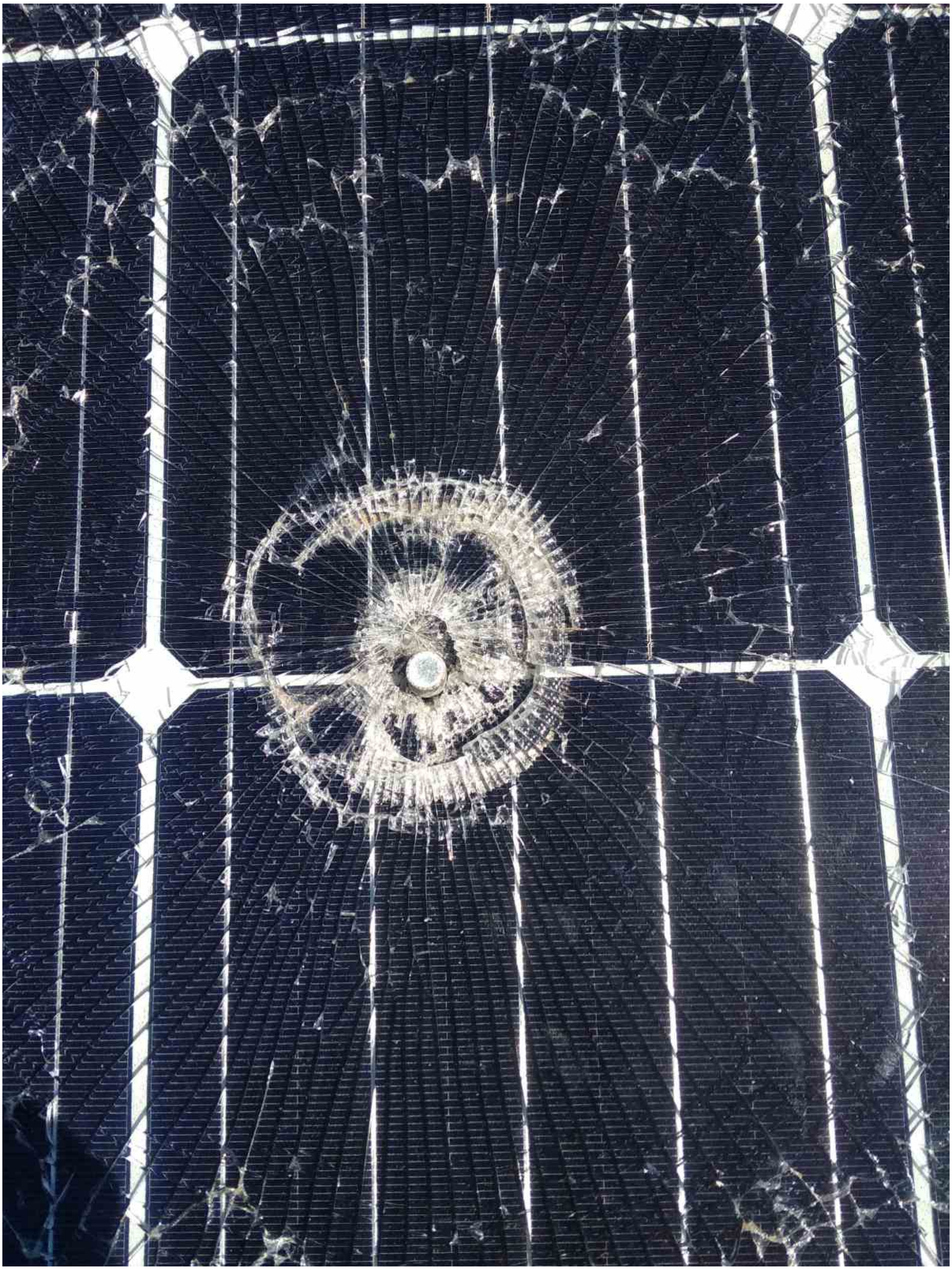

Figure 2. Damaged solar module.

installations, small hydroelectric power plants) is located, which should not be forgotten in today's conditions. These sources, in most cases, do not require the use of fossil fuels and the entire infrastructure associated with fuel supply. RES can work in off-grid mode. Dispersion of distributed energy sources of electrical energy is a valuable indicator – it is impossible to damage them at the same time, and in practice it is impractical (the costs far exceed the cost and benefits). Each individual distributed source of electrical energy does not represent "systemic, or national" value, but the whole point is that all of them (small sources) together are valuable as a general source of energy in Ukraine. Such sources are able to provide electricity to nearby settlements with all infrastructure (hospitals, communications, etc.) for an almost unlimited time [9]. High penetration of RES in distributed power grid forces up to development of effective means of researching reasons of over-voltages in these networks and find approach to decrease over-voltages.

3. Analysis of 10 kV network damage data

The main causes of damage to 10 kV transmission lines are

- in overhead networks: damage to line poles, overlapping and damage to insulation on poles, damage to cable couplings during the transition of overhead lines to cable lines;
- in cable networks: damage to insulation at substations, damage to terminal and connecting couplings, damage during excavation works in the vicinity of the cable route, damage to cables.

The most vulnerable element of the power grid to internal overvoltages are cables, in particular, the places where they are connected to each other and to other elements of the grid. Therefore, a significant proportion of damage is associated with overvoltages during single-phase earth faults in cable networks (according to data, 77 percents of the number of damages [8]).

The analysis shows that the causes of damage to cable lines in most cases are: mechanical damage, factory defects, defects in the installation of couplings, violations of the technology of laying cable lines, and extreme operating conditions. Single-phase short circuits occur, as a rule, in places of defects in the insulation of cable lines and substation equipment due to aging of the insulation, failure to comply with the technology of manufacturing insulating structures at factories, standards and instructions for the installation and operation of equipment, as well as mechanical damage, which at the time of their occurrence leads to only a partial reduction in electrical strength.

Internal overvoltages often occur during transients from an intermittent arc and are dangerous for the insulation of electrical installations due to their duration and the breadth of coverage of the network associated with the damage site.

The process of insulation aging is greatly influenced by technological and operational factors. Technological factors include hidden defects in manufacturing and installation; the use of materials that do not meet the requirements for them; changes in the modes of thermal vacuum treatment of insulation after manufacturing; and crimping defects. Operational factors, if we exclude accidents caused by human error, include, first of all, overloads: short-circuit currents, switching and lightning surges. Overloads lead to the emergence of various kinds of defects, which then develop in the operating mode. The complex organic insulation of cables, connecting and termination cable couplings tends to accumulate defects. The effect of over-voltage on such insulation is accompanied by a decrease in electrical strength, which is not restored to its original state after the over-voltage ceases. After the over-voltage action, the cumulative development of weaknesses (defects) occurs, and a breakdown may occur with further accidental over voltages. An inter-phase short circuit occurs, as a rule, after multiple accidental actions. In a complex set of locations with weakened insulation, a network disturbance occurs when at least one location with the most weakened insulation (with the largest defect) finally loses its electrical strength.

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To ensure sufficiently high operational reliability, measures must be taken to strengthen the insulation and limit over-voltages. The second way, as less costly, is more profitable.

The most frequent type of internal over-voltage in 6-35 kV networks is over-voltage associated with single-phase earth faults, accounting for up to 80 percents of all types of accidents (figure 3). In recent years, the average specific rate of damage to grids due to electrical causes has increased by about an order of magnitude and, according to operational experience, taking into account the equipment of power grids that was broken during tests, is more than 100 damages for every 100 km of the grid per year. In the overwhelming majority of cases (up to 90 percents of the number of disruptions to the normal operation of the network), the damage begins with an insulation breakdown to the ground, and then more than half of them (up to 70 percents under the circumstances) develop into inter-phase short circuits or multi-location insulation breakdowns with group failure of electrical equipment.

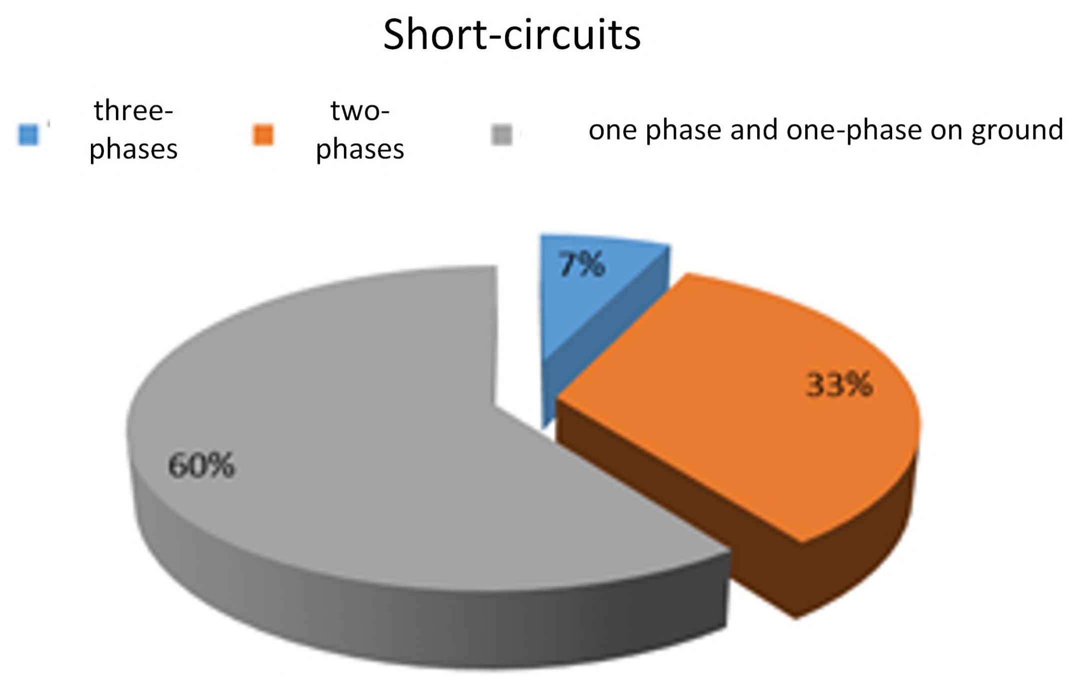

Figure 3. Diagram of damage to power lines with a voltage of 6-10 kV.

The biggest danger is posed by arc over-voltages that occur in the network when the arc burns in an intermittent manner at the point of breakdown of phase insulation to earth, as the arc can damage the insulation and cause a two- or three-phase short circuit. According to some reports, about 60 percents of earth faults in these electrical networks are of this nature. The extinguishing and ignition of an intermittent arc causes complex transients, the intensity of which, as operating experience shows, depends on such factors as arc characteristics, capacity, inductance, circuit resistance, etc. In networks with a predominance of cable lines, outages due to the transition of a single-phase fault to an inter-phase fault reach 70 percents of the number of outages. An increase in earth fault current leads to an increase in the probability of single-phase fault to inter-phase fault directly at the point of arc burning.

From the experience of operating 6-10 kV cable networks, there are repeated cases of multi-location insulation breakdowns under operating voltage. There are cases of simultaneous breakdowns in 4-5 points of the lines. First, the presence of insulation breakdowns under operating voltage indicates an insufficiently high level of insulation. Secondly, the presence of multiple breakdowns indicates the existence of over-voltages. Thus, despite significant insulation reserves, the accident rate of 6-35 kV networks due to internal over-voltages is quite high. Therefore, the development of effective means of studying over-voltages in these networks and means of reducing them is currently relevant [10].

The goal of the research is to investigate the causes of false activations of relay protection of 10 kV power transmission lines during double earth faults using MATLAB. Therefore, the purpose of research is relevant.

Data on the features of operation, damage and damage protection of 10 kV lines are given in [8]. Features of the protection of equipment of electric power systems are considered in [11]. The processes of changing currents and voltages in lines with an isolated neutral and protection against their damage during earth faults are discussed in [7, 12].

Relay protection in 6–10 kV power grids s with an isolated neutral (including a neutral grounded through an arc extinguishing reactor) must be provided with relay protection devices against multi-phase circuits and single-phase circuits to the ground). Protection against multi-phase short-circuits should be provided in a two-phase version and connected to the same phases throughout the network of a given voltage to ensure that in most cases of double earth-faults, only one point of damage is turned off. Protection should be performed with one, two or three relays depending on the requirements of sensitivity and reliability. As a rule, two-stage current protection should be installed on single lines with single-sided power supply from multi-phase circuits, the first stage of which is made in the form of current cut-off, and the second – in the form of maximum current protection with an independent or dependent time delay characteristic.

On non-reactor cable lines with one-way power, departing from the busbars of power plants, current cut-offs must be performed without time delay and the area of their effect must be determined from the condition of short-circuit shutdown, accompanied by residual voltage on the busbars of the specified power plants below 0.5–0, 6 nominal. To fulfill the specified condition, it is allowed to perform non-selective protection in combination with Automatic Transfer Switch (ATS) or automatic circuit reclosers (ACRs) devices, which fully or partially correct the non-selective effect of protection. It is allowed to install the specified cut-offs also on the lines departing from the busbars of substations and feeding large synchronous electric motors. Current cut-offs are not allowed on lines whose switches are not designed to turn off the short-circuit to the reactor. On double-fed single lines with or without bypass connections, as well as on lines forming part of a ring network with a single point of supply, it is recommended to use the same protections as on single-sided fed lines, performing them directional if necessary. In order to simplify protections and ensure their selective action, it is allowed to use automatic division of the network into radial sections at the time of damage with subsequent automatic restoration.

4. Simulation of the mode of a three-phase 110/10 kV network in MATLAB

A model of a three-phase 110/10 kV network was built using Matlab. Three lines are connected to the 10 kV bus, on which switches Q1, Q2, Q3 are installed. The input switch is marked QBB. The load of the lines is 600, 500, 400 kW, according to lines 1-3. The model simulates single-phase short circuits on lines with the first (line 1) and second breaker (line 2). During the simulation of a short-circuit at a given time, a transient process occurs, the model allows analyzing the parameters of this process, considering the processes in a certain period of time. With the help of models of measuring devices and the “Scope” element, we can study the graph of current and voltage at the desired moment in time in the examined node of the circuit. For example, by installing, after the input switch, a three-phase measuring device connected to the “Scope” element, the model allows you to obtain a current oscillogram (figure 4). The network diagram is shown inlabelThe diagram of the studied network Consider figure 4, “Scope” built an oscillogram of three-phase current: yellow line – phase A, blue – phase B, orange – phase C.

In the study was simulated the short circuit of phase A of the first line and the short circuit of phase B of the second line at a time of 0.2 s. The maximum value in phase A, the first line,

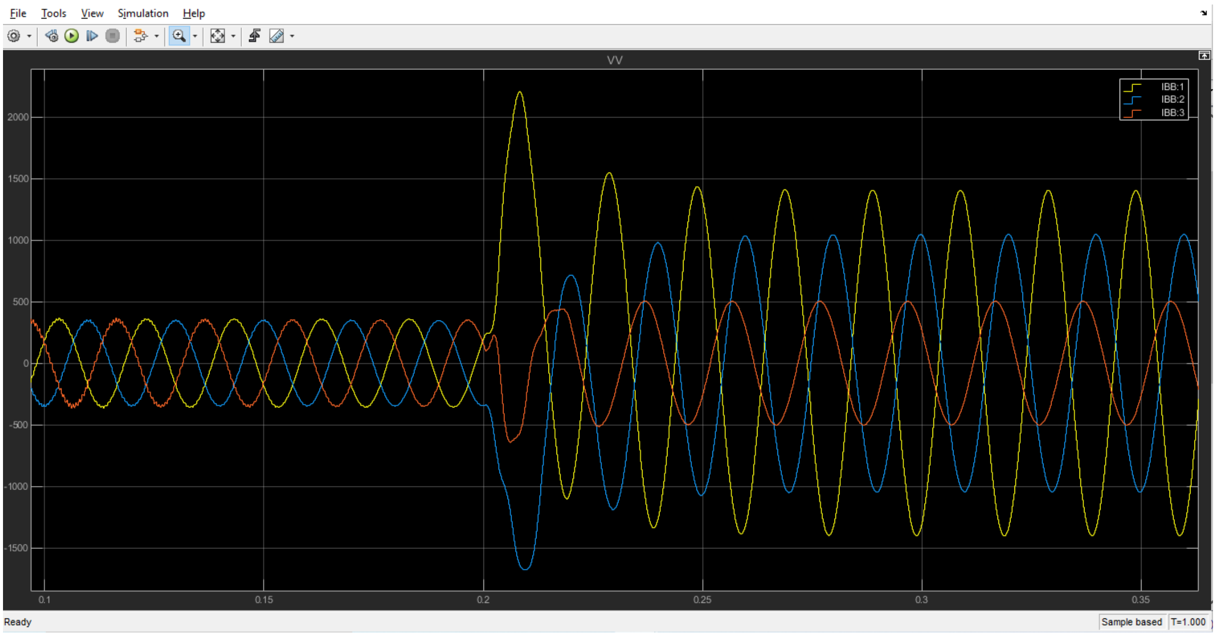

Figure 4. Current oscillogram obtained using "Scope".

is 2300 A, and in phase B, the second line, 1905 A. On the input switch, the same values were equal to 2206 A and 1680 A, respectively. Values in short-circuit mode have increased by 30 – 40 times.

The calculated values of the maximum current protection settings for phase A of the first line, phase B of the second line and for the input switch are shown in table 1.

Table 1. The calculated values of the maximum current protection settings for phase A of the first line, phase B of the second line and for the input switch.

Name	The calculated values of the maximum current protection
A	300.3
B	264.5
Input	1322.75

For clarity, a graph of the K coefficients is plotted (figure 6), showing how many times the short-circuit current is greater than the short-circuit current.

The graph shows that the excess of the current in the damaged overhead line over the over-current protection set-point of this overhead line, during double faults, can occur earlier, by 0.004 s, than the increase in the current in the input switch for certain values of the overhead line and short-circuit parameters. Therefore, it is necessary to set a delay in the operation of the input circuit breaker so that it does not trip the undamaged lines. The graph shows what value of the delay time in the operation of the recloser should be set (taking into account the time of the selectivity degree, to ensure error-free operation of the protection. The time selectivity degree of the recloser takes into account the operating time of the circuit breakers and the errors of the time relay. According to the graph, the delay time is 0.05 s, as the transient process ends and the steady-state short-circuit mode begins.

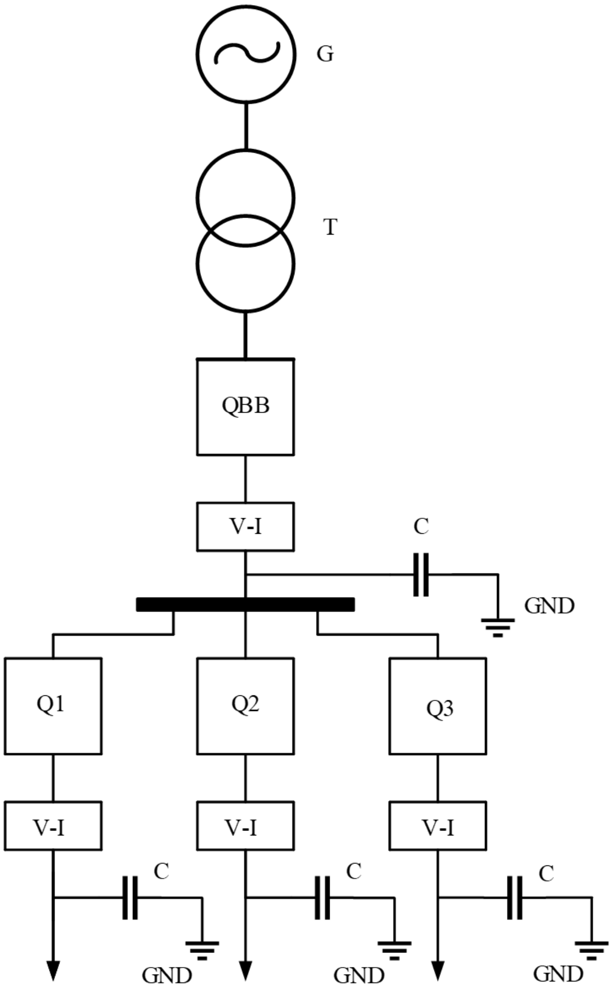

Figure 5. The diagram of the studied network.

5. Conclusions

According to the results of the analysis of double short circuits in the power line, the current in the damaged power line exceeds the set point of the relay protection system of this power line, during double short circuits, may occur earlier, by 0.004 s. Than the current increases in the input circuit breaker for certain values of the power line and short-circuit parameters. Based on the results of calculations of the parameters of the 10 kV power transmission line considered in the work, it was determined that the tripping current is equal to 300 A, and the power supply acting on the input switch of the substation to which the 10 kV power line is connected is equal to 1323 A. For the considered examples of operation of the power transmission line in the first case will happen selectively, and in the second case, the protection will not work correctly. First, the input switch will turn off, and then the feeder switch. Turning off the input switch de-energizes not only damaged lines, but also healthy lines. Therefore, the conditions for ensuring the selective operation of the power transmission system for the investigated variant of the power transmission line are not always provided. In order to reduce false disconnections of 10 kV power lines, it is necessary to increase the operating time of the relay protection acting on the input circuit breaker at the substations on the 10 kV side so that the 10 kV input circuit breaker operates later than any of the feeder circuit breakers of the investigated substation.

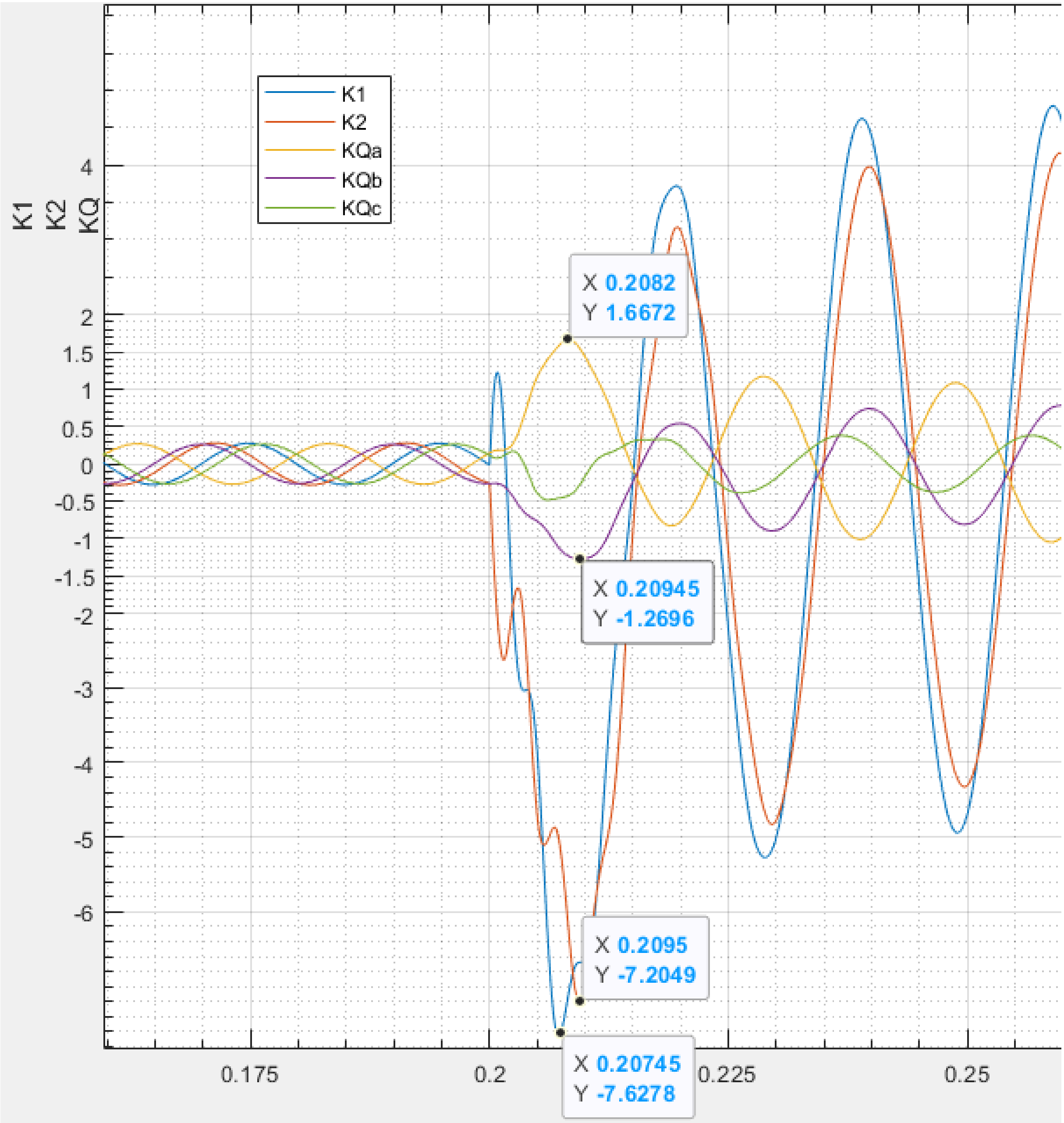

Figure 6. Graph of the coefficients K1, K2, KQ(a, b, c) as a function of time.

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The postwar perspective of ammonia production in Ukraine

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The postwar perspective of ammonia production in Ukraine

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Abstract. After the war, a favorable situation may arise in Ukraine not only for the restoration of ammonia production but also for its increase and the implementation of new state-of-the-art technologies that make it possible to improve energy efficiency and reduce CO_2 emissions. The authors have identified the prerequisites for the post-war ammonia production development in Ukraine. The authors have presented the optimization model to minimize primary investments for reaching given ammonia production and specific CO_2 emissions. The sharp increase in required investments is observed when new production capacities are needed. For existing capacities that will be undamaged after wartime the most effective mitigation measure both economically and environmentally is carbon storage and capture. The main directions of further study were outlined. The paper aims to analyze the prerequisites for post-war ammonia production in Ukraine and develop an optimization model to minimize primary investments in the quantitative and qualitative development of ammonia production in Ukraine.

1. Introduction

Ammonia production is a highly energy-intensive process consuming around 1.8% of global energy output and producing as a result about 500 million tonnes of carbon dioxide (about 1.8% of global carbon dioxide emissions) [1]. Ammonia synthesis is significantly the largest carbon dioxide emitting chemical industry process. Along with cement, steel, and ethylene production, it is one of the 'big four' industrial processes where a decarbonization plan must be developed and implemented to meet the net-zero carbon emissions target by 2050. About 70% of ammonia is used for fertilizers, while the remainder is used for various industrial applications, such as plastics, explosives, and synthetic fibers. While the use of ammonia as a fuel shows promise in the context of clean energy transitions, this application currently remains nascent.

International Energy Agency has developed Ammonia Technology Roadmap which presented three scenarios of ammonia production till 2050 [2]: the Stated Policies Scenario (STEPS), Sustainable Development Scenario (SDS) and Net Zero Emissions by 2050 Scenario (NZE). Table 1 presents the main characteristics of these scenarios.

After the war, a favorable situation may arise in Ukraine not only for the restoration of ammonia production but also for its increase and the implementation of new state-of-the-art technologies that make it possible to improve energy efficiency and reduce CO_2 emissions. The paper aims to analyze the prerequisites for post-war ammonia production in Ukraine and develop an optimization model to minimize primary investments in the quantitative and qualitative development of ammonia production in Ukraine.

Table 1. The characteristics of Scenarios from [2] (% in 2050 relative to 2020).

Scenarios	Description	Ammonia	CO_2 emissions
STEPS	Reflects the sector's current trajectory, influenced by existing and announced policies. All regions are on track to reach current BAT energy performance levels soon after 2050, as plants are upgraded and replaced to meet stringent energy performance standards in several regions and to maintain competitiveness in others. Continued improvements in process energy efficiency are outweighed by increasing demand for ammonia, pushing up overall energy consumption.	40%	14%
SDS	Presents a pathway with regional detail that puts the energy system as a whole on a trajectory compatible with the goals of the Paris Agreement. The main shifts in energy consumption stem from the deployment of innovative near-zero-emission technologies. In this scenario 83% of the total electricity demand for ammonia production in 2050 is used to produce hydrogen via electrolysis, with the remainder appying ancillary units (e.g. air separation units) and carbon capture equipment.	25%	73%
NZE	The faster pace of emissions decline is achieved primarily through more rapid deployment of innovative near-zero-emission technologies. By 2050, 41% of ammonia is produced via electrolytic hydrogen. CO_2 capture for permanent storage from ammonia production would rise to 100 Mt CO_2 by 2050, with almost 50% of the fossil-based capacity equipped with CCS.	23%	96%

2. The current state of ammonia production in Ukraine

Five big industrial plants could produce ammonia in Ukraine (table 2). Only two are in operation now due to wartime, the high price of natural gas, etc. The annual ammonia production capacity totals approximately 5.7 mln tonnes.

All plants use steam methane recovery technology for ammonia production in Ukraine. Ammonia production, corresponding CO_2 emissions and CO_2 emission factor are presented at the figure 1 [6, 7].

At the figure 1 CO_2 emission factor was estimated at the national level. Recently, it has become possible to obtain data on natural gas consumption and CO_2 emissions at the installation level. In view of the future entry of Ukraine to the EU and accession to the EU Emission trading system the Law of Ukraine dated 12.12.2019 No. 377-IX "On Principles of Monitoring, Reporting and Verification of Greenhouse Gas Emissions" (hereinafter referred to as the Law on MRV) have entered into force from January 1, 2021 [8]. The Resolution of the Cabinet of Ministers of Ukraine dated 23.09.2020 No. 880 [9] set the requirements for the operators to register in the Unified MRV Register if they are subject to monitoring, reporting, and verification. All installations of ammonia production are included in the list of activities under this Resolution.

Table 2. The big industrial plants of ammonia production (t per year).

Plant	Owner	Capacity	Comments
PJSC "Odesa Portside Plant" [3]	State Property Fund of Ukraine	1240000	In September 2021, the PJSC stopped the production of chemical products due to the high natural gas price in Ukraine and the low price of ammonia on the world market
PJSC "Azot" (Cherkasy) [4]	OSTCHEM Group DF	963000	In operation
PJSC "Rivneazot" [4]	OSTCHEM Group DF	420000	In operation
PrJSC "Severodonetsk Azot Association" [4]	OSTCHEM Group DF	1020000	The activity was blocked due to hostilities
JSC "Dniproazot" [5]	State Property Fund of Ukraine	584000	The JSC stopped the production of chemical products due to the high natural gas price in Ukraine
PJSC "Concern Stirol" [4]	OSTCHEM Group DF	1470000	From 2014 "Concern Stirol" is located in the temporarily occupied territory and does not produce ammonia

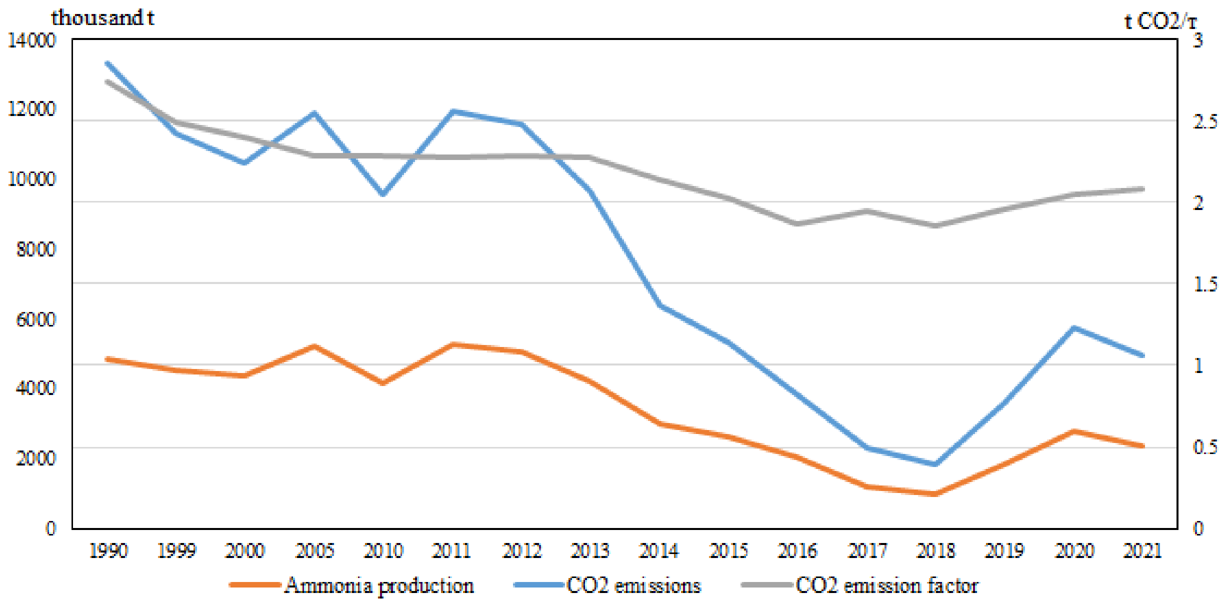

Figure 1. Ammonia production and corresponding CO_2 emissions in Ukraine.

Operators should carry out monitoring and reporting following the requirements specified in the Procedure for Monitoring and Reporting on Greenhouse Gas Emissions, approved by Resolution No. 960 of the Cabinet of Ministers of Ukraine dated September 23, 2020 [10].

According to Article 16 of the Law on MRV information on quantitative and qualitative indicators of greenhouse gas emissions is open and access to it cannot be restricted.

Operators of installations had to report their emissions starting in 2021. Unfortunately, due to the martial law, the Ukrainian government adopted the Law of Ukraine dated 03.03.2022 No. 2115-IX "On the Protection of the Interests of Subjects Submitting Reports and other Documents during the Period of Martial Law or the State of War" [11].

According to Article 1.1 of this Law legal entities submit accounting, financial, audit reports and any other documents, the submission of which is required following the norms of current legislation in the documentary and/or in electronic form, within three months after the termination or cancellation of martial law or the state of war for the entire period of failure to submit reports or the obligation to submit documents.

Therefore many installation do not report their emissions during wartime. After the war ends plant-specific information will become available.

3. The prerequisites for post-war ammonia production in Ukraine

Ukraine would have significant advantages from ammonia production in both the existing conditions and given the appropriate CO_2 emission factors.

The previous section states that the ammonia production capacities in Ukraine totaled 5.7 mln t before the wartime. It should be mentioned that ammonia fertilizer production facilities also exist in Ukraine. The shortage of fertilizers on world markets leads to an increase in their cost, reaching the highest levels since 2012 in 2021 [2].

Another advantage for Ukraine is the presence of a large branched system of gas pipelines and preserved wells, that is, there is the necessary infrastructure for carbon storage and capture. Ukraine has an 800-kilometer ammonia pipeline "Horlivka – Odesa" with a capacity of up to 2.5 million tons per year and a significant fleet of railway and road tankers for transporting ammonia.

Ukraine is one of the largest exporters of food. In 2021, the largest percentage of Ukraine's exports was accounted for by agricultural and food products, namely 40.7%. The leaders of this industry are oil as a processed product, cereals (wheat, corn, etc.), sugar, confectionery, vegetables and fruits, and flour products. During the wartime food and agricultural products remained the largest part of Ukrainian exports, accounting for 53% in 2022. After the wartime Ukraine will need fertilizers to provide intensified agriculture development.

Appropriate legislation has already been implemented in Ukraine, which creates a normative and regulatory field for the commercial circulation of ammonia.

Ukraine would have an advantage from the participation in the EU Emissions trading system and a significant benefit from the export of ammonia given the appropriate CO_2 emission factors.

In present the Carbon Border Adjustment Mechanism (CBAM) holds substantial implications for ammonia production, particularly in the context of the European Union's ambitious decarbonization strategies. CBAM, as a carbon pricing framework, seeks to establish a fair competition landscape between EU producers and their global counterparts by attaching a price tag to carbon emissions associated with imports, including ammonia. The overarching objective is to incentivize international trading partners to curtail their manufacturing emissions. For ammonia producers, CBAM ushers in specific stipulations. Under the preliminary CBAM proposal, European ammonia producers continue to benefit from free carbon credit allowances, in line with the benchmarks outlined in the EU Emissions Trading System. This approach encourages EU-based ammonia producers to maintain their emissions below benchmark levels, thereby shielding them from carbon leakage risks, where competitively priced imports from less regulated nations could undermine the competitiveness of EU producers. Furthermore, CBAM enforces comparable carbon costs on ammonia importers as those faced by EU-based producers. Importers are obliged to procure and surrender CBAM certificates for emissions exceeding benchmark levels. This policy provides advantages to importers, if their emissions fall below the benchmarks, allowing them to evade additional costs associated with CBAM certificates. This arrangement proves advantageous for European ammonia producers, guaranteeing a level

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playing field and the opportunity to capitalize on their "free" allowances, contingent upon their emissions remaining beneath the benchmark [12].

In the broader economic spectrum, industries affected by CBAM, such as ammonia in the fertilizer production sector, confront challenges stemming from elevated energy prices and inflationary pressures. These factors culminate in diminished production capacities and escalated production expenses. These circumstances underscore the necessity for policies that bolster corporate investments and mitigate excessive short- to medium-term outlays.

In summation, while CBAM aspires to cultivate a sustainable and equitable trading milieu, it simultaneously introduces an array of challenges and ramifications for ammonia producers, both within and outside the EU. The mechanism serves as a catalyst for the reduction of carbon emissions in ammonia production but introduces intricacies into market dynamics, exerting an impact on both EU producers and importers.

4. Results and discussion

General Energy Institute of National Academy of Sciences of Ukraine has long been conducting research related to the reduction of greenhouse gas emissions in the energy [13,14], industrial [15], coal [16, 17], oil and gas [18] and transport [19] sectors, etc.

The authors have been developing a set of optimization models with different objective functions (primary investments, cost of ammonia production, CO_2 emissions, etc.), different levels (national, plant), periods (implementation stage, life cycle period), etc.

The authors have been developing a database of ammonia production technologies. At the present stage, this database includes the following technologies: steam methane recovery (SMR), auto-thermal reforming (ATR); carbon capture and storage (CCS), and electrolysis. Techno-economic indicators of ammonia production technologies are presented at the table 2 [2, 7, 20].

Table 3. Techno-economic indicators of ammonia production technologies.

Indicators	Units	SMR	CCS	ATR+CCS	Electrolysis
Typical plant capacity	thous. t/year	220-1205	220-1205	220-1205	10-510
Capital investments	thous \$/t	1.91	0.14	2.11	2.36
O&M cost	mln \$/year	50	10	55	65
CO_2 emissions	t/t	1.81	0.12	0.19	0.00

Below the authors consider the optimization model to minimize primary investments for reaching given ammonia production and specific CO_2 emissions.

The objective function is as follows:

$$Investments = \sum_{i=1}^{5} InvRest_i + \sum_{i=1}^{5} \sum_{j} Prod_{ij} * Inv_{ij} + \sum_{k=1}^{new} Prod_k * Inv_k \rightarrow \min.$$

A set of constraints are as follows:

$$TotalProduction = \sum_{i=1}^{5} \sum_{j} Prod_{ij} + \sum_{k=1}^{new} Prod_k,$$

$$EmissionFactor = \frac{\sum_{i=1}^{5} \sum_{j} Prod_{ij} * Emission_j + \sum_{k=1}^{new} Prod_k * Emission_k}{Production}.$$

For each i:

$$\sum_j Prod_{ij} \leq ProductionCapacity_i,$$

where $Investments$ – primary investments for existing and new (if any) ammonia production plants, i – index for existing plants, j – index for production technology at the existing plants, $InvRest$ – investments needed to restore existing plants (at present these values cannot be estimated), $Prod_{ij}$ – ammonia production at the existing plant i by production technology j, Inv_{ij} – matrix of specific investments for transition from production technology i to production technology j, $Prod_k$ – ammonia production at the new plant k, Inv_k – specific investments to implement production technology k, $TotalProduction$ – the given value of total ammonia production at the existing and new (if any) plants, $Emission_j$ – specific CO_2 emissions for production technology j at the existing plants, $Emission_k$ – specific CO_2 emissions for production technology k at the new plants (if any), $ProductionCapacity_j$ – ammonia production capacity at the existing plant i (table 2).

The results of the calculation for different production volumes (restoring before the war, two times increase and three times increase) and specific CO_2 emissions (the average in EU and the benchmark for CBAM) are given at the table 4.

Table 4. Preliminary estimation of primary investments to ammonia production.

Ammonia production, thous t	Specific CO_2 emissions, t/t	Primary investments, mln $
2000	1.85	24.00
2000	1.57	57.60
4000	1.85	48.00
4000	1.57	115.20
6000	1.85	69.03
6000	1.57	164.79

The sharp increase in required investments is observed when new production capacities are needed. For existing capacities that will be undamaged after wartime the most effective mitigation measure both economically and environmentally is carbon storage and capture.

For existing plants that will be damaged after the war, it is necessary to estimate the level of destruction of each plant and make a decision about the expediency of restoring previous production technology or implementing new state-of-the-art technology.

The authors are planning the following research:

- The further development and clarification of the technology database is needed. For instance, ammonia is produced from nitrogen (N_2) and hydrogen (H_2), not only synthetically but also naturally. Whilst the synthetic ammonia production routes have developed over the past century, some organisms in nature fix nitrogen in the form of ammonia with nitrogenase [21–24]. Other sources of fixed nitrogen are atmospheric deposition, recycling of crop residues, and animal manures such as guano. The authors are planning to estimate the availability of nitrogen-fixed products in Ukraine and corresponding technologies.
- The authors are looking for installation reports under MRV system. The use of plant-specific data on energy consumption and emission factors gives a possibility to obtain more accurate results from the optimization model at the national level.
- The authors are planning to develop a set of optimization models. For example, after the war ends it is of primary importance to minimize the levelized cost of ammonia production at the national level.

5. Conclusions

After the war, a favorable situation may arise in Ukraine not only for the restoration of ammonia production but also for its increase and the implementation of new state-of-the-art technologies that make it possible to improve energy efficiency and reduce CO_2 emissions.

The authors have identified the following prerequisites for the post-war ammonia production development in Ukraine.

- The ammonia production capacities totaled 5.7 mln t before the wartime.
- the presence of a large branched system of gas pipelines and preserved wells, that is, there is the necessary infrastructure for carbon storage and capture.
- Ukraine has an 800-kilometer ammonia pipeline "Horlivka – Odesa" with a capacity of up to 2.5 million tons per year and a significant fleet of railway and road tankers for transporting ammonia.
- Ukraine is one of the largest exporters of food. After the wartime Ukraine will need fertilizers to provide intensified agriculture development.
- Ukraine has nitrogen fertilizer facilities while the shortage of fertilizers on world markets is observed.
- Appropriate legislation has already been implemented in Ukraine, which creates a normative and regulatory field for the commercial circulation of ammonia.
- Ukraine would have a significant benefit from the export of ammonia given the appropriate CO_2 emission factors.
- Ukraine would have an advantage from the participation in EU Emissions trading system given the appropriate CO_2 emission factors.

The authors have presented the optimization model to minimize primary investments for reaching given ammonia production and specific CO_2 emissions. The sharp increase in required investments is observed when new production capacities are needed. For existing capacities that will be undamaged after wartime the most effective mitigation measure both economically and environmentally is carbon storage and capture.

The authors have outlined the main directions of further study: development and clarification of the technology database, use of plant-specific data on energy consumption and emission factors, development of new optimization models, in particular minimizing the levelized cost of ammonia production at the national level.

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Prospects for autonomous low-power renewable energy communities

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Abstract. This article explores strategies for ensuring the autonomous operation of Renewable Energy Communities (RECs) in Ukraine, aligning with the ongoing reform in the country's energy sector. The reform emphasizes the implementation of promising autonomous decentralized systems, potentially leading to the establishment of RECs. These initiatives aim to incorporate low-capacity sources in providing electricity during autonomous conditions or outages. Examining data on small electricity producers reveals the prevalence of solar power plants, the emergence of micro-hydro plants, and limited representation of wind power. The article also underscores the increasing significance of biogas in electricity production. Furthermore, it explores the formation of RECs as a contemporary decentralized solution, requiring a thorough analysis of sustainability for autonomous operation. The utilization of various generation types in the structure of RES (renewable energy sources) communities enables the adaptation of electricity generation to dynamic conditions, ensuring system resilience in the face of failures or challenges associated with a predominant generation source. The core focus shifts towards optimizing existing hybrid systems encompassing different renewable energy sources. This involves analyzing load and capacity distribution, technological profiles, and integration strategies for RECs into the power grid, ultimately contributing to the enhancement of Ukraine's energy security. The proposed approach involves mathematical modeling of low-power hybrid renewable systems that derive electricity from RECs. This modeling incorporates generation characteristics, objective functions, and constraints to facilitate multi-criteria decision-making. The results underscore the significance of exploring diverse scenarios and combinations of generating sources, taking into account resource potential, electricity generation variability, operating costs, and other factors. This holistic approach allows for the optimization of the RES community structure, striking a balance between reliability and cost considerations.

1. Introduction

In the contemporary Ukrainian energy landscape, there is a discernible trend towards augmenting the role of RES. The primary emphasis lies in advancing solar and hydropower, particularly through the establishment of mini- and micro-hydroelectric power plants (HPPs). Conversely, wind energy exhibits limited representation, attributed to its elevated capital requirements and the intricacies associated with implementation in smaller facilities. Solar power plants (SPPs) within the 10–50 MW range claim a substantial market share due to their

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scalability, accounting for 3.135 MW of installed capacity. Following closely are plants with capacities between 5 and 10 MW, contributing 1.192 MW to the installed capacity (table 1) [1].

Table 1. RES market segmentation based on power plant capacities.

Power MW	< 1	1–5	5–10	10–50	50–100	100–200	> 200
Number of plants, pcs.	492	337	168	188	15	2	2
Total capacity, MW	184.8	846.3	1 191.7	3 134.6	1 102.8	362.8	569.4

In the realm of RES technologies employed by small-scale electricity producers, a notable divergence emerges compared to the broader market landscape. Analogous to the overall electricity market structure, SPP) dominate among small RES power plants, boasting a total installed capacity of 121.991 MW. This contrasts with the larger market, where wind farms rank second in installed capacity. In the domain of small electricity producers, however, wind farms hold the penultimate position, with a total installed capacity of 1.7 MW. Conversely, the second position among small RES power plants is claimed by small and micro-hydroelectric power plants, amassing a total installed capacity of 47 MW.

A discernible pattern emerges when examining the technological composition of the small RES market categorized by capacity:

- SPPs predominate across all capacity categories;
- mini- and micro- HPPs secure the second position across all capacity categories;
- Wind Power Plants (WPPs) are notably absent in categories up to 300 kW, attributable to technical and economic considerations, such as the relatively high cost of turbines and substantial maintenance efforts.

These outcomes align with various factors:

- photovoltaic technology's high standardization and minimal spatial requirements facilitate diverse installations on the ground, roofs, or building facades.
- the prevalence of small and micro-hydroelectric power plants results from the refurbishment of Soviet-era hydroelectric facilities on small rivers.
- the capital-intensive nature of wind power generation technologies renders them economically unviable on a smaller scale.

As of 2020, table 2 delineates regional leadership in total capacity for RES power plants with an installed capacity of less than 1 MW, with Vinnytsia, Khmelnytskyi, Ivano-Frankivsk, Kyiv, and Zakarpattia regions emerging as frontrunners. While other Ukrainian regions contribute noteworthy capacities of small-scale RES, their collective total remains below 7 MW.

In addition to advancing solar energy, the utilization of biogas for electricity production is gaining traction in Ukraine [2]. As of 2022, several noteworthy developments have transpired in the bioenergy sector:

- bioenergy plants boast an installed capacity of 140 MW, encompassing facilities ranging from 125 kW to 26 MW.
- the aggregate electricity generation in 2022 amounts to 505.4 GWh.
- the count of operational biogas plants stands at 83.

Table 2. Technological composition of small renewable energy power plants: regional installation structures.

Region	Regional installed capacity in megawatts (MW)			
	WPP	Mini-micro HPP's	SPPs	Total
Vinnytsia	0	4.83	17.33	22.16
Dnipropetrovska	0	0.13	11.34	11.47
Transcarpathian	0	6.71	6.01	12.72
Ivano-Frankivsk	0.6	2.44	12.19	15.23
Kyiv	0.45	2.02	9.37	11.84
Lviv	0	0.62	8.59	9.21
Ternopil	0.66	2.64	8.9	12.19
Khmelnytsky	0	7.55	8.29	15.85
Cherkasy	0	3.15	6.55	9.7

These bioenergy initiatives contribute to regional energy autonomy, with many projects generating electricity primarily for internal consumption. The progression of renewable energy sources enhances supply chain reliability, bolsters overall energy security, and fosters local economic growth, thereby fortifying community resilience.

Against the backdrop of ongoing energy sector reforms in Ukraine, there exists a compelling imperative to cultivate distributed generation and align with the tenets of the 4th Energy Package [3]. Concurrently, European nations, guided by the National Energy and Climate Plan and various directives (e.g., Renewable Energy Directive 2018/2001/EU, Directive on common rules for the internal market in electricity EU/2019/944, Energy Performance of Buildings Directive 2018/844), are instituting decentralized structures in their energy systems and markets. The emergence of RECs [4], contingent upon the renewable sources within specific territories [5], epitomizes a contemporary solution. The operation of these communities forms decentralized autonomous energy systems, a subject of growing relevance in recent years [6, 7].

In the present context, the vitality and evolution of our country's energy sector necessitate a more profound analysis. This entails not only scrutinizing the prospects of autonomous decentralized systems with the potential formation of RECs but also delving into the sustainability of these systems, particularly in conditions of autonomy or blackouts [8].

Hence, a pressing imperative is to investigate the optimization of existing hybrid power systems [9]. These systems, incorporating diverse RES types, respond to challenges such as power supply instability induced by natural disasters, aging infrastructure, and damage during conflicts. The paramount goal is to enhance the reliability and autonomy of energy systems. This becomes especially pivotal after severe damage to energy infrastructure and amid significant uncertainties in regional energy supply, particularly in areas directly impacted by hostilities.

This study addresses the optimization of small RES power plant load and capacity distribution, technological profiling, and their potential integration into resilient hybrid systems. The overarching objective is to devise strategies for optimizing their operation, thereby fortifying the country's energy security. Subsequent research will strive to identify the most effective methodologies and approaches to modernize and heighten the level of autonomous operation in energy systems, minimizing dependence on centralized networks and maximizing RES potential, with significant societal and economic implications.

2. Definition of objectives, constraints, and solution methodology

Following research on hybrid renewable systems [10–13], a mathematical model (figure 1) was developed by the authors. This model encapsulates the operational dynamics of low-power hybrid renewable energy systems, considering mode characteristics of generation sources, a set of objective functions, and technical and economic constraints. The model facilitates optimal load distribution among system components. Specific optimization methods are employed to address the challenge of achieving optimal load distribution among generation sources. The model's response to changes in objective functions and constraints illuminates its behavioral variations.

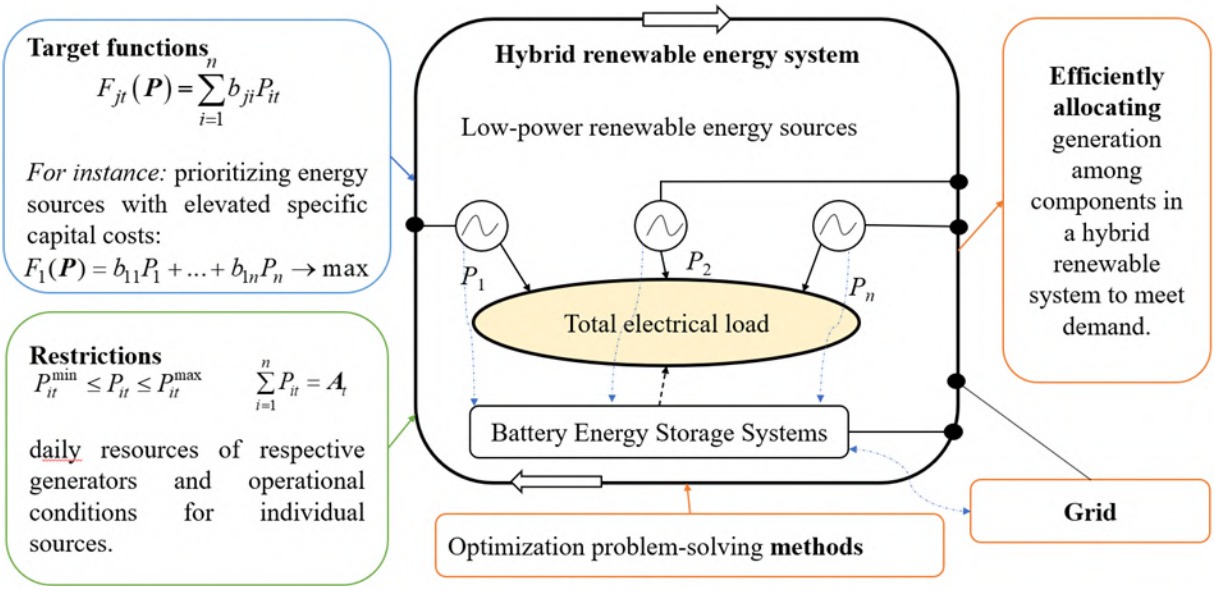

Figure 1. Mathematical model for the operation of a RES.

In addressing the challenge of optimizing the utilization of energy resources, a set of objective functions is initially defined, and the problem constraints are identified. When deliberating on optimal decision-making under the specified conditions, priority is given to the economic considerations associated with the operation of a low-capacity RES. This encompasses the proximity of RES, technical specifications of community components, and the environmental implications of employing various controlled or uncontrolled electricity generation sources. The functions defining the optimal efficiency of a small-scale RES community are articulated in user-friendly language.

It is evident that, in specific contexts, the roster of target functions may be subject to limitation or expansion. The objective is to formulate a list of target functions that effectively characterize various participants in the electricity market, including suppliers and operators. Hence, the list remains open-ended. The structure of each objective function is as follows:

$$F_{jt}(P)=\sum_{i=1}^{n} b_{ji}P_{it}, P=\{P_1,\ \ldots,\ P_i,\ \ldots,\ P_n\}, \tag{1}$$

where, b_{ji} represents the coefficients of respective additional objective functions; P_{it} denotes the proportional contribution of the i-th renewable energy source to the electric load during each time period t; $j=1$, ..., m – the total number of objective functions; n represents the number of factors (i.e., generating energy sources); and t signifies a specific time period (e.g., a particular hour of the day).

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In certain objective functions, the coefficient, for instance, may assume values such as: 1) the specific operating costs; 2) the number of hours of maximum utilization; 3) the level of harmful emissions into the atmosphere, etc.

During the optimization problem-solving process, some of the aforementioned objective functions necessitate minimization, while others require maximization. Mathematically, the formulation of the problem for the objective functions is as follows, aiming to determine for individual periods t.

$$F_{jt}\left(P\right) \rightarrow \underset{P\in L}{\operatorname{extr}}, j = 1, , m, P = \left\{P_1,\ ...,\ P_i,\ ...,\ P_n\right\}, \tag{2}$$

where m – number of objective functions; on condition if

$$L = \left\{P \in R^n\right\}, L \subseteq \Omega, \tag{3}$$

where Ω – Pareto optimal solution space [14–16].

Practically, most multicriteria optimization problems are inherently heuristic. Therefore, in the development of methods for solving such problems, several pivotal issues must be considered [14–16]. Firstly, the optimality principle in these problems should elucidate the context in which the optimal solution surpasses all other valid options and provide guidelines for discovering this optimal solution. Secondly, local criteria in these tasks often exhibit different physical natures and are measured on distinct scales, complicating direct comparisons of results for each criterion. Consequently, normalization is necessary to standardize the dimensionality of local criteria to a unified, dimensionless measurement scale. Thirdly, the analysis of numerous practical tasks underscores those different local criteria carry varying levels of importance in achieving the final result. Hence, when defining the optimality principle and the solution space, consideration should be given to the fact that certain local criteria hold higher priority and necessitate the incorporation of a degree of their 'importance'. Insufficient clarity in defining optimal solutions poses a key methodological challenge in addressing multicriteria optimization tasks. The practical application of multicriteria decision-making procedures across a broad spectrum of problems [16] has demonstrated the effectiveness of the Bellman-Zadeh method, grounded in the mathematical principles of fuzzy set theory. Advantages of this method include: 1) the simultaneous consideration of quantitative and qualitative factors, with the ability to distinguish their levels of importance; 2) a clear and logical definition of the optimality criterion in terms of maximizing the achievement of all target functions; 3) automatic attainment of a solution guaranteed to belong to the Pareto region, making it the definitive resolution to the problem.

The application of the Bellman-Zadeh method in a fuzzy environment for making optimal decisions aligns with the principle of reliable outcomes and provides a constructive approach to achieving harmonious solutions. The Bellman-Zadeh method stands as an efficient, computationally sound, yet demanding method in obtaining solutions from the Pareto region in the analysis of multicriteria models [14, 16].

According to this approach, each evaluated objective function $F_j(X), j = 1, , m$ is replaced by a fuzzy objective function or a fuzzy set of the form

$$A_k = \left[A,\ \mu_{A_k}\left(X\right)\right], \tag{4}$$

where $\mu_{A_k}\left(X\right)$ is the membership function of the fuzzy function A_k [14, 16]; L represents the trade-off domain.

The membership function of a fuzzy set is an extension of the characteristic (indicator) function of a conventional set. In fuzzy logic, this function quantifies the extent to which each element in the space belongs to a specific fuzzy set. The membership function serves as a subjective measure of fuzziness, as assessed by experts through a survey, indicating the degree of correspondence of an element X to the concept formalized by the fuzzy set A_k.

The fuzzy solution to problem D is derived as outlined in [10,12] $D = \bigcap_{k=1}^{m} A_k$, yielding the following membership function:

$$\mu_D(X) = \min_{k=1,\ \dots,\ m} \mu_{A_k}(X), X \in L. \tag{5}$$

This decision may be construed as an ambiguous directive, introducing uncertainty regarding the selection of a specific alternative. Consequently, there arises a necessity to address and resolve this ambiguity. Multiple methods and techniques exist for mitigating this uncertainty. A prevalent approach, proposed in [16], involves selecting the alternative with the highest degree of membership in the fuzzy decision. In essence, the alternative is identified based on the following condition:

$$\max \mu_D(X) = \max_{X \in L} \min_{k=1,\ \dots,\ m} \mu_{A_k}(X). \tag{6}$$

These alternatives are referred to as maximizing alternatives.

The final decision in the optimization process is determined by the point corresponding to the maximum value of the membership function.

$$X^0 = \arg \max_{X \in L} \min_{k=1,\ \dots,\ m} \mu_{A_k}(X). \tag{7}$$

When addressing an optimization decision-making problem using the aforementioned approach, the formation of the membership function holds significance. These objective functions should aptly capture the essence of the respective evaluation objectives.

Specifically, the following membership functions can fulfill these conditions, structured as follows:

- For the objective functions to be minimized:

$$\mu_{A_k}(X) = \left[\frac{\max\limits_{X \in L} F_j(X) - F_j(X)}{\max\limits_{X \in L} F_j(X) - \min\limits_{X \in L} F_j(X)} \right]^{\lambda_j}. \tag{8}$$

  For optimization problems involving minimization of the objective function, the membership function attains large values at smaller evaluation function values. At the point of minimum, it reaches its maximum value of one.

- For objective functions to be maximized:

$$\mu_{A_k}(X) = \left[\frac{F_j(X) - \min\limits_{X \in L} F_j(X)}{\max\limits_{X \in L} F_j(X) - \min\limits_{X \in L} F_j(X)} \right]^{\lambda_j}. \tag{9}$$

  In optimization problems involving maximization, the membership function is expected to assume a value of one at the maximum value of the estimated objective function, where λ_j – is an indicator reflecting the importance of the k-th evaluation function, often determined through experimental or expert means.

Figure 2 illustrates the implementation of these concepts in the multi-criteria load balancing method for generating energy sources within the RES community.

The multi-criteria resource allocation algorithm encompasses multiple stages executed for each designated time period t, as detailed in [14, 15].

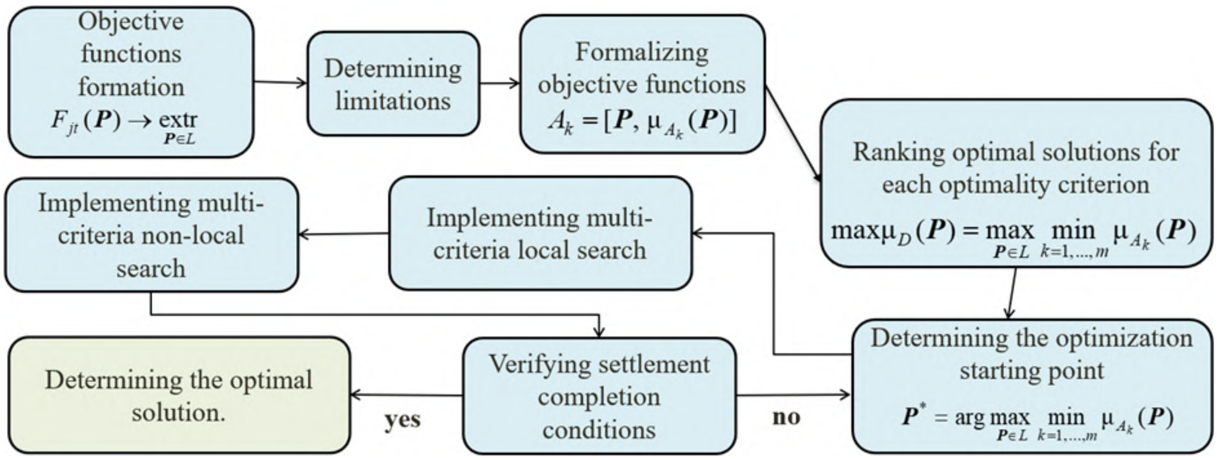

Figure 2. Modified resource allocation method.

3. Results

To simulate the autonomous operation of the RES community, we employed data on electricity consumption [17] by consumers in a specific region of Ukraine over a 24-hour period. The consumer load profile utilized for modeling is depicted in figure 3.

The autonomy of the analyzed RES community is achieved by eliminating power flows with the external power system. This requires that all consumed electricity be generated exclusively from its own facilities, necessitating an increase in their installed capacity.

The problem at hand involves determining the minimum installed capacity for each type of generator, aiming to minimize energy intake from the external grid for each hour of the billing day. To address this, we simulate the optimal loading mode of various generators, seeking the total daily generation while considering the overall power flow with the external power system. The simulation involves varying the installed capacity of generators within a predefined range as a percentage of the current capacity. The minimum value of installed capacity resulting in the minimum power flow with the external power system is selected from the obtained results.

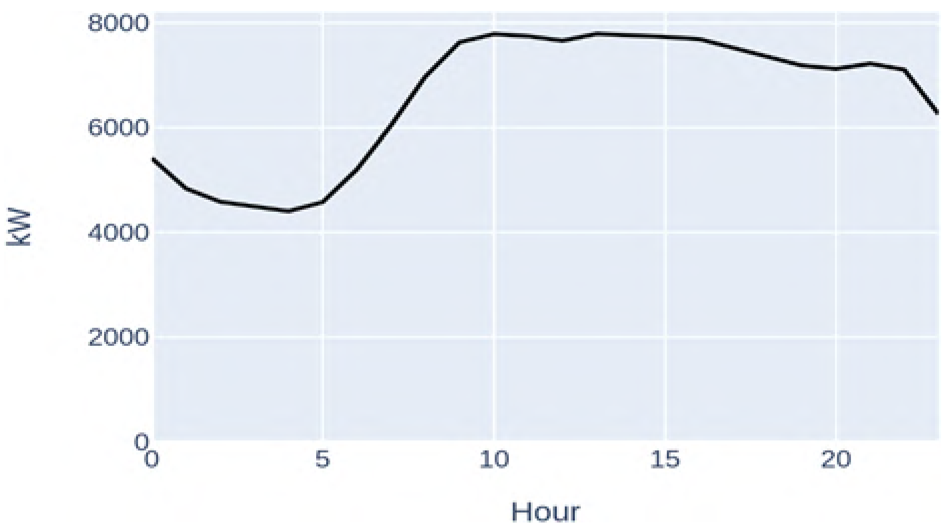

Figure 3. Electricity consumption graph in the RES Community.

Table 3. Capacity ratios among different RES types in RES community structures.

Proposed RES community structures	biogas plants	SPPs	micro-HPPs
Structure 1	44 %	27 %	29 %
Structure 2	33 %	32 %	35 %
Structure 3	38 %	23 %	39 %
Structure 4	28 %	27 %	45 %

In experimental calculations, we assessed an electric power system, comprising low-capacity RES in close territorial proximity, providing electricity to a specific community. Potential generation sources include SPPs, micro-HPPs, and biogas plants.

Modeling was conducted for four distinct RES community structures, delineated by the ratio of installed capacities among different types of generation (SPPs, micro-HPPs, biogas plants). The ratios employed in the modeling are outlined in table 3.

Initially, let's examine the autonomy scenario for the RES community by augmenting the installed capacity of biogas generators. We will conduct simulations with variations in the installed capacity of the plants within the range of 50-200% of the current capacity. The results of the modeling figure 4.

As evident from the graph, achieving autonomy in a type 1 power system structure necessitates a 175% increase in the installed capacity of biogas generators. For a type 3 structure,

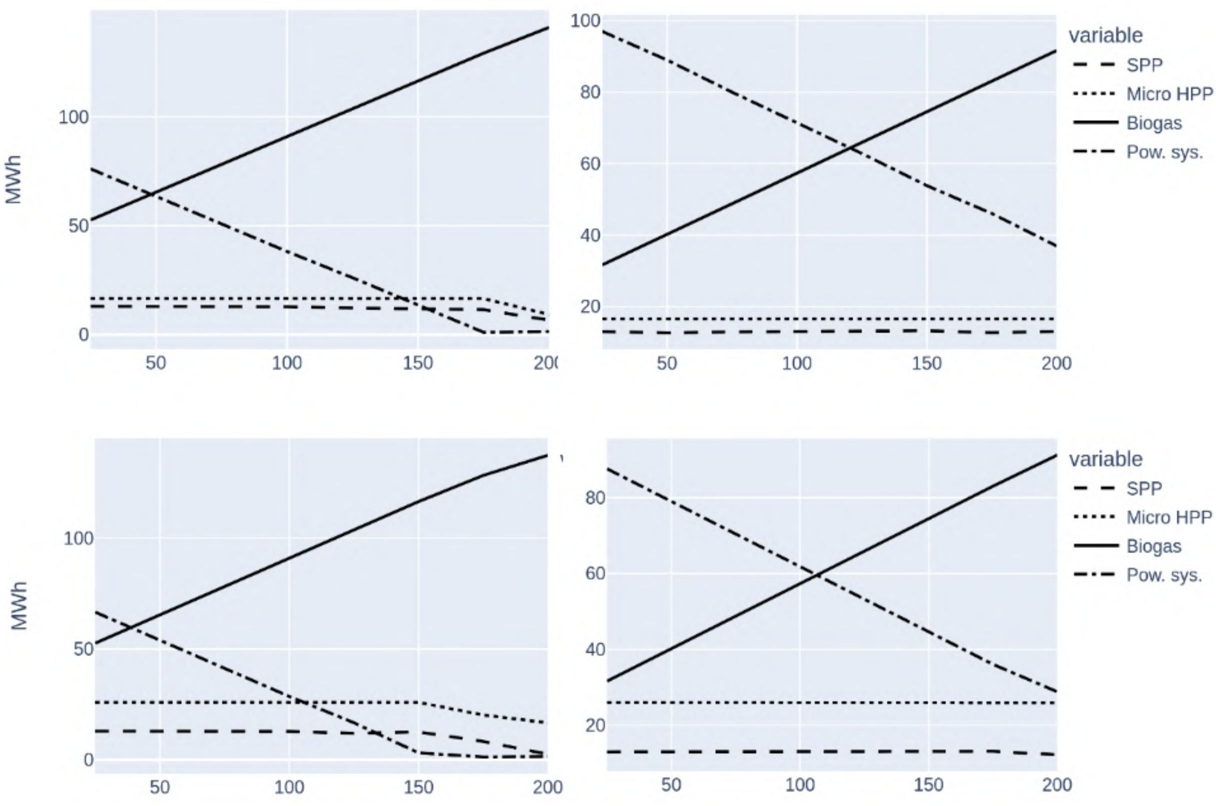

Figure 4. Relationship between the total daily electricity generation and the percentage increase in biogas generator installed capacity.

a 150% increase is required. However, autonomy remains unattainable for structures with types 2 and 4, even with a 200% increase in the installed capacity of biogas generators.

Figure 5 illustrates the results of optimizing the operation mode of a RES community with a type 1 structure under initial conditions (figure 5*a*) and the conditions of achieving autonomy through an increased installed capacity of biogas generation (figure 5*b*).

Next, let's explore the autonomy scenario for the RES community by augmenting the installed capacity of SPPs. Simulations will be conducted with variations in the installed capacity of the plants within the range of 150-500% of the current capacity. The modeling results are presented in figure 6.

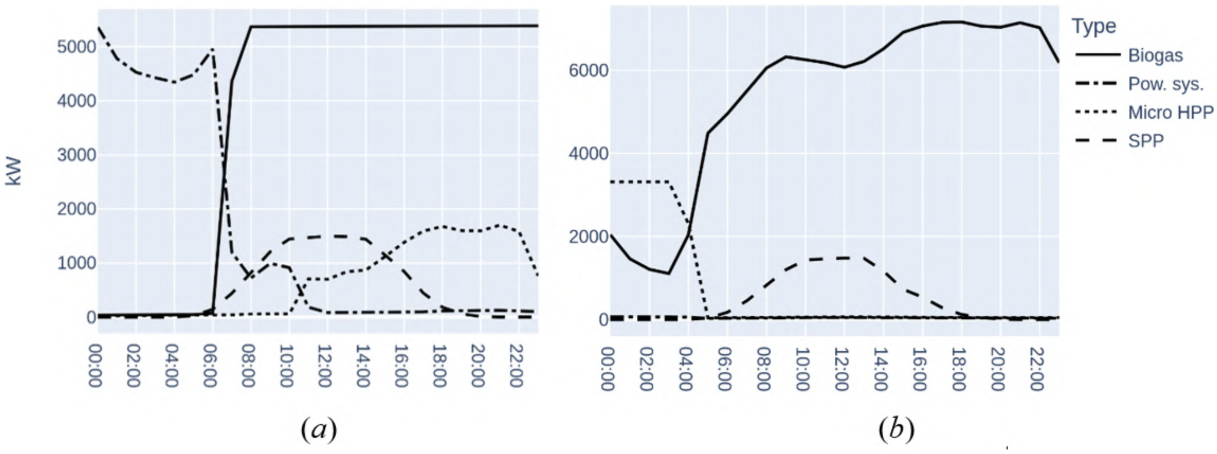

Figure 5. Optimization results for the operation mode of RES community structure type 1.

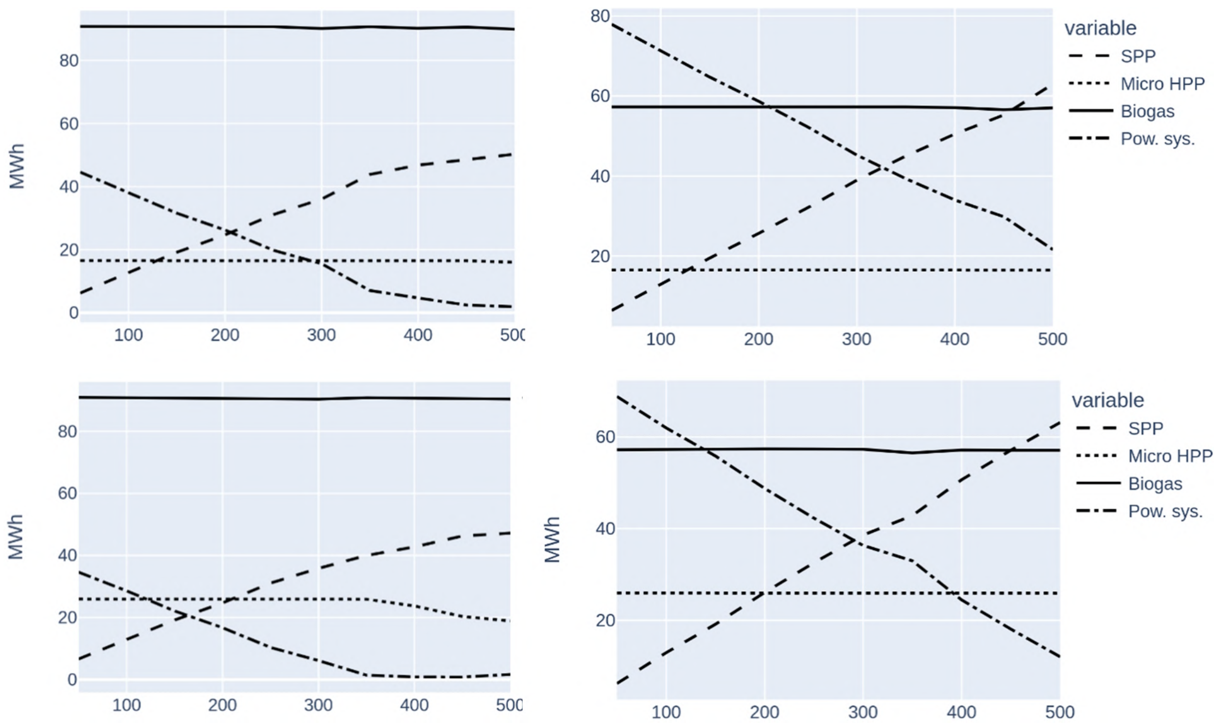

Figure 6. Relationship between the total daily electricity generation and the percentage increase in SPP installed capacity.

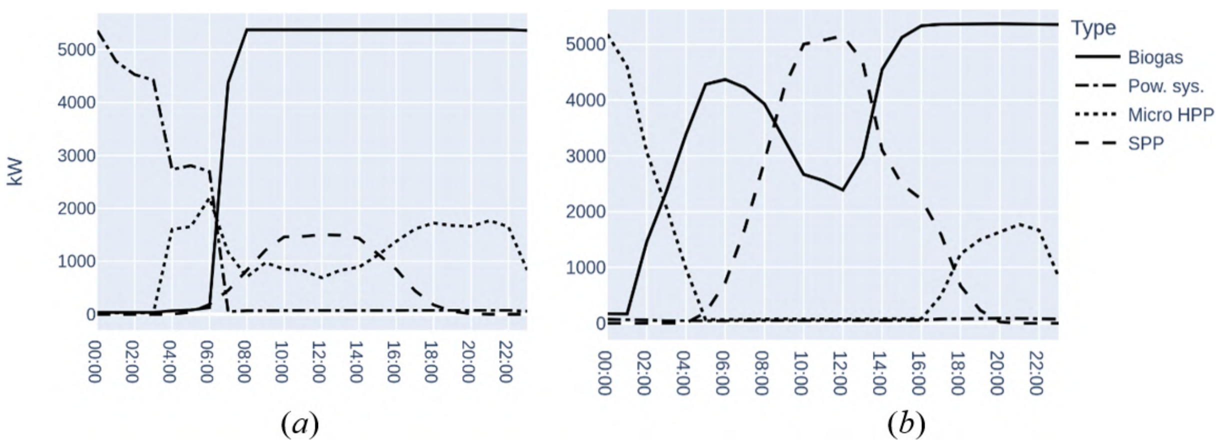

Figure 7. Optimization results for the operation mode of RES community structure type 3.

As evident from the graph, achieving autonomy in a type 1 power system structure requires a 450% increase in the installed capacity of SPPs. For a type 3 structure, a 350% increase is needed. However, autonomy remains unattainable for structures with types 2 and 4, even with a 500% increase in the installed capacity of the SPP.

Figure 7 illustrates the results of optimizing the operation mode of a RES community with a type 3 structure under initial conditions (figure 7*a*) and the conditions of achieving autonomy through an increased installed capacity of SPPs (figure 7*b*).

Several uncertainties impact the optimal outcomes, encompassing natural components, grid configuration, load fluctuations, and other factors. Despite these variables, the use of generation and consumption profiles enables the execution of simulations, facilitating the derivation of optimal solutions.

4. Conclusions

To ensure the autonomous operation of the RES community in the considered region of Ukraine, it is imperative to augment the installed capacity of generating facilities to meet peak loads, eliminating the need for external grid energy. Simulation across four types of RES community structures reveals autonomy feasibility for the first and third structures, requiring substantial increases in biogas generator capacity (up to 175% for the first structure and up to 150% for the third).

For structures with types 2 and 4, autonomy remains unattainable even with a 200% increase in biogas generator capacity, prompting the exploration of alternative measures for energy independence or the integration of additional generation sources. A similar trend emerges with an increased installed capacity of SPPs. Autonomy is achieved for the first structure with up to a 450% increase and for the third structure with up to a 350% increase. However, structures with types 2 and 4 fail to achieve autonomy, even with a 500% increase in SPP capacity.

The optimal pathway to autonomy involves adapting the RES community with a predominant share of biogas generation in the first structure and SPPs in the third structure. Nevertheless, these substantial capacity increases necessitate significant investments and may encounter limitations due to technical, economic, or environmental constraints.

The modeling results underscore the importance of exploring diverse scenarios and combinations of generating sources, considering their resource potential, electricity generation variability, and operating costs. This approach facilitates the optimization of the RES community structure, achieving a balance between reliability, cost, and environmental considerations.

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Revisiting mathematical model of the process of self-destruction of outburst-hazardous coals under hydrodynamic impact

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Revisiting mathematical model of the process of self-destruction of outburst-hazardous coals under hydrodynamic impact

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Abstract. One of the options of self-destruction process model of outburst-hazardous coal seams under hydrodynamic impact (HDI) in the conditions of mines in the Donbas central region is considered. The model is based on the results of a comprehensive study of the parameters of the HDI process: mass and coal recovery factor; flow rate of technological boreholes and volume of extracted gas; the calculated degree of the massif degassing and the HDI degassing index from the coal hardness and the natural gas content of outburst-hazardous coal seams. The solution to this problem is connected with the lack of a model for coal destruction during HDI, which leads to an avalanche-like self-destruction of outburst-hazardous coals with the generation of methane. The phenomenon of methane generation is considered in the "coal-gas" system, which is a complex globular organization of macromolecules of outburst-hazardous coals. The model allows to consider the process of development of additional stresses around new formations and theoretically substantiate the presence of an additional source of gas release. To determine the stress-strain state, a solution to the spatial problem of elasticity theory is proposed for n successively arranged cylindrical cavities under the internal pressure action in an isotropic and homogeneous infinite medium is proposed. The dynamic component of the process is determined by the component of the stressed state of the elastic medium under the action of variable load and inertia forces in stressed gas-filled media. The research results are used in the development of technology of active degassing and coalbed methane production by hydrodynamic impact method.

1. Introduction

One of the types of catastrophic man-made natural phenomena is sudden release of coal and gas during mining operations at great depths. The solution to this problem is related to the study of the relationship between methane and coal matter. The results of such studies are sufficiently presented in the scientific and technical literature and do not require explanation. Herewith, it is known that the results of laboratory studies of outburst-hazardous coals do not always correspond to the truth, as they are carried out on transformed coal samples. This discrepancy is especially evident during hydrodynamic impact (HDI) on outburst-hazardous coal seams [1,2]. Some features of HDI and the self-destruction process were considered in paper [3].

The structure of outburst-hazardous coals, and these are grades of coal "K" and "Zh" *(Medium volatile bituminous and Hight volatile bituminous A)*, unlike other grades, have a globular supramolecular assembly (SMA) of the coal substance and are considered as a coal-gas medium formed by nature, or a "coal-gas" system [2, 4]. Transformation processes in such systems are accompanied by new formations with the generation of gases, mainly methane. It is practically impossible to create an analogue of coal-gas medium for its study in laboratory conditions. Therefore, the results of mine experiments are of particular importance in presenting this natural phenomenon.

Hydrodynamic impact (HDI) on outburst-hazardous coal seams through boreholes is one of the methods for initiating such a transformation process. The effective use of HDI in order to prevent gas dynamic phenomena (GDP) during the opening of outburst-hazardous seams, during degassing of abutment pressure zones (APZ), during the extraction of methane from a coal rock massif through boreholes drilled from the surface, and the subsequent analysis of study results made it possible to establish a number of new, previously unknown features of the destruction of outburst-hazardous coals. In the process of study, the following were established: the phenomenon of the occurrence of dynamic loading of a gas-saturated rock massif: the phenomenon of spontaneous destruction of an outburst-hazardous coal seam; the pattern of destruction of porous medium [1].

It is known from solid mechanics that the cause of layer-by-layer destruction of solid bodies is the manifestation of tensile stresses at the boundary of the plastic and elastic zones [5]. In this case, it does not really matter how the plastic state of the borehole contour rocks is achieved. It is important that the unloading process occurs relatively quickly. The manifestation of tensile stresses at the boundary of the plastic and elastic zones is confirmed by the appearance of ring cracks on models made of homogeneous isotropic materials. However, when studying such models, the question of the presence of any gaseous media in the system was not considered.

When solving problems of hydrodynamics in a rock massif, when the brittle, plastic and elastic properties of bodies manifest themselves in the studied medium (rock layers), different models of the processes are considered. Thus, the mathematical description of the processes and phenomena that occur during HDI is based on the model of layer-by-layer destruction of coal [6]. When developing this model, liquid filtration processes were considered, on the basis of which the parameters and modes of the method were established. In the process of mining operations, HDI modes were improved, the gas-dynamic state of coal seams and the stress-strain state of the coal rock massif were studied, new methods and their technological schemes were developed, and the results of studies [1, 6, 7], were analyzed. Herewith, the models of liquid filtration and layer-by-layer destruction of coal during HDI have not changed. As a result, the processes established during HDI are: spontaneous destruction of the coal seam; gas emissions in volumes that exceed the calculated values by an order of magnitude or more; self-supported destruction of coal; the formation of the zone of the near-borehole gas reservoir and the active degassing of the massif have not received scientific justification.

Solving problems of this level is possible using numerical methods. For example, in the paper [8] the processes of fluid filtration and deformation of a porous medium are considered in the finite element packages ABAQUS and MSCMarc. The authors [9] use the numerical modeling method to solve unsteady hydrodynamic equations. The paper [10] discusses the features of conducting a computational experiment using the finite element method when calculating a multi-parameter system "rock massif – combined bracing". In paper [11], problems related to coal gasification in underground conditions are solved.

The search for a mathematical model that can explain the process of avalanche-like self-destruction of the coal-gas system is also related to studies of the parameters of wave and resonance phenomena that manifest themselves during HDI. In this regard, the article [12] is of interest, in which the problem of propagation of acoustic waves in a pre-deformed elastic half-space that interacts with a layer of viscous fluid is considered. Since the problem is solved in an analytical form, the media models have a classical character, i.e. they are based on the application of both the theory of elasticity and the Navier-Stokes equations. However, it should be taken into account that when applying such a solution to the conditions of the rock massif, some of its provisions should be simplified.

2. Problem statement

In order to describe the processes occurring in the massif around the borehole during HDI, it is necessary to find a model that will scientifically substantiate the process of self-destruction of the coal-gas system and methane generation.

The necessity of solving this problem is associated with the high efficiency and reliability of the HDI method, as well as the lack of a model for coal destruction during HDI, which leads to an avalanche-like self-destruction of outburst-hazardous coals with the generation of methane. The phenomenon of methane generation is considered in the "coal-gas" system, which is a complex globular assembly of macromolecules of outburst-hazardous coals. Therefore, the model should reflect the processes of new formations and the development of additional stresses around defects on the coal surface, which theoretically justify the presence of additional sources of gas release.

The purpose of the paper is to study the hypothesis of justification of additional gas release from the borehole by creating additional stress concentrators in its vicinity. Development of an adequate mathematical model to describe the process of initiating and maintaining self-destruction of outburst-hazardous coals under hydrodynamic impact through boreholes.

3. Methods

When considering models of the process of self-destruction of outburst-hazardous coal seams during HDI, analytical and experimental study methods were used. To describe the processes of additional methane generation from a coal massif in the borehole vicinity by organizing stress concentrators, the numerical solution of a spatial axisymmetric problem of elasticity theory is considered by applying the Papkovich-Neuber functions.

4. Results

4.1. Problem solution

From the conclusions formulated in paper [3] we highlight that the lack of theoretically based solutions in determining the components of dynamic loading of a coal-gas medium during HDI does not allow us to substantiate the mechanism of its self-destruction process. At the same time, the effect of initiating self-destruction of coal in a stressed-strained coal-gas system and its maintenance by the HDI method is widely used in the mines of the Central region of Donbas [1, 6, 7].

The high efficiency and reliability of HDI, established in practice, are confirmed by the results of scientific study and their reliability. The established patterns of process development are based on the results of studies of the coal recovery coefficient (C_R), the flow rate of technological boreholes (Q), the volume of extracted gas (V), the degree of degassing of the massif (k), the coal hardness (f) and the natural gas content (X) of outburst-hazardous coal seams. The correlation between the parameters C_R, f, X and k_p, f, X is confirmed by the determination coefficient R^2 from 0.95 to 0.98.

This gives grounds for the development of a mathematical model of the process of self-destruction of outburst-hazardous coals under hydrodynamic impact.

4.2. Solving the problem with stress concentrators in cracks

The intensity of the destruction process can be controlled either by changing the pressure gradient or by changing the length of the working chamber. The influence of pressure drop in the borehole cavity was studied in a practical way. To obtain answers to the questions posed, it is necessary to present the results of solving the dynamic problem of a pressure pulse impact on the borehole vicinity. In this paper such a problem was not considered due to the complexity of its solution. It is proposed to consider changes in the parameters of the working chamber by solving the following analytical model [13].

It is known that increasing the cavity length leads to an increase in the front of liquid action and a decrease in the destruction process intensity. Reducing the length, on the contrary, leads to intensification of deformation processes in the disturbance zone. The use of several sequentially located chambers will increase the efficiency of the process and the emergence of additional stress gradients in the surrounding space.

For a significant length of the working chamber, the Lamé solution is usually used [14]. In case of short chambers, it is not advisable to use it due to the large error. Therefore, at the first stage, a cylindrical cavity was considered, which is divided into short chambers of the same length equal $2l$ with a distance between them equal $2d$ (figure 1).

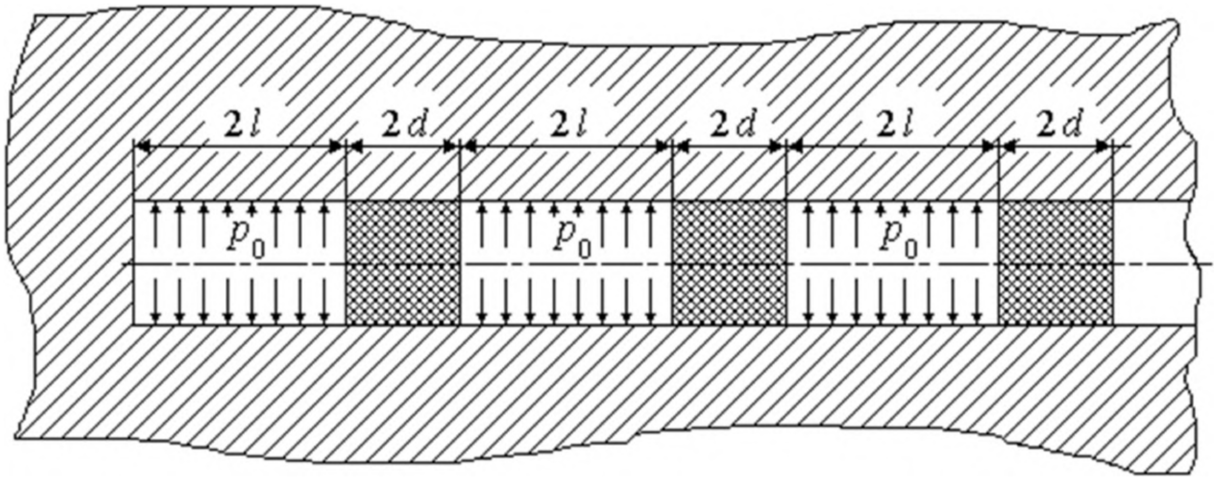

Figure 1. Layout of cylindrical chambers.

Pressure p_0 acts on the side surface of the chambers from the inside. The problem in this formulation is axisymmetric with cylindrical coordinates r, ϕ, z and is solved using the Papkovich-Neuber functions in the form [14, 15]

$$\begin{aligned} u &= 4(1-v)B_r - \frac{d}{dr}(rB_r + zB_z + B_0), \\ w &= 4(1-v)B_z - \frac{d}{dz}(rB_r + zB_z + B_0), \end{aligned} \tag{1}$$

where u, w – radial and axial displacement components; r, z – radial and axial coordinates; B_r, B_z – projections of the harmonic vector B onto the corresponding coordinate directions; B_0 – harmonic scalar; v – Poisson's ratio.

The algorithm for finding the functions B_r (r, z) and B_0 (r, z) can be found in [16]. In this case, after some transformations we get

$$\begin{aligned} u &= [(4(1-\nu)K_1(\beta\rho) + \beta\rho K_o(\beta\rho))C_2 + \beta K_1(\beta p)D_2]\cos\beta\zeta, \\ w &= [pK_1(\beta p)C_2 + K_o(\beta\rho)D_2]\beta\sin\beta\zeta, \end{aligned} \tag{2}$$

The constants C_2 and D_2 are determined from the boundary conditions and can be formulated as follows for an even number of cavities

$$\sigma_r(\zeta)\Big|_{\rho=1} = \begin{cases} p_0 \quad \text{at } (2k-1)(b+\delta)-b<|\zeta| \\ |\xi| < (2k-1)(b+\delta)+b, \quad k=1,\ldots,n/2; \\ 0 \quad \text{in other cases} \end{cases} \tag{3a}$$

for an odd number of cavities

$$\sigma_r(\zeta)\Big|_{\rho=1} = \begin{cases} -p_0 \quad \text{at} \quad 2k(b+\delta)-b<\zeta<2k(b+\delta)+b, \\ k=0,\pm1,\ldots,\pm(n-1)/2; \\ 0 \quad \text{in other cases} \end{cases} \tag{3b}$$

where $d = d/r_0$; $b = l/r_0$.

Another condition for any number of cavities will be the condition that the tangential stresses on the surface of the cylindrical cavities are equal to zero:

$$\tau_{rz}\Big|_{\rho=1} = 0 \tag{4}$$

After performing a number of operations, partial solutions will have the form

$$\begin{aligned} \sigma_r &= -\frac{2G}{r_0}\left[\left((3-2\nu)\beta K_0(\beta\rho) + \left(4(1-\nu)\frac{1}{\rho}+\beta^2\rho\right)K_1(\beta\rho)\right)C_2\right. \\ &\qquad\qquad\qquad\left. +\beta\left(\beta K_0(\beta\rho)+\frac{1}{\rho}K_1(\beta\rho)\right)D_2\right]\cos\beta\zeta, \\ \sigma_z &= \frac{2G}{r_0}\left[\left(\beta^2\rho K_1(\beta\rho)-2\nu\beta K_0(\beta\rho)\right)C_2+\beta^2K_0(\beta\rho)D_2\right]\cos\beta\zeta, \\ \sigma_\phi &= \frac{2G}{r_0}\left[\left((1-2\nu)\rho K_0(\beta\rho)+4(1-\nu)\frac{1}{\rho}K_1(\beta\rho)\right)C_2+\frac{\beta}{\rho}K_1(\beta\rho)D_2\right]\cos\beta\zeta, \\ \tau_{rz} &= -\frac{2G}{r_0}\left[\left(\beta\rho K_0(\beta\rho)+2(1-\nu)K_1(\beta\rho)\right)C_2+\beta K_1(\beta\rho)D_2\right]\beta\sin\beta\zeta. \end{aligned} \tag{5}$$

General solutions can be found in the form of Fourier integrals of the form

$$\int_0^\infty \sigma_i(\rho,\zeta,\beta)P(\beta)\,d\beta, \quad i=\overline{1,4} \tag{6}$$

where $\sigma_1 = \sigma_r$, $\sigma_2 = \sigma_z$, $\sigma_3 = \sigma_\phi$, $\sigma_4 = t_{rz}$,

$$P(\beta) = \frac{2}{\pi}\int_0^\infty \sigma_r(\zeta)|_{(\rho=1)}\cos(\beta\zeta)d\zeta =$$

$$= \begin{cases} \frac{4p_0}{\pi}\sum\limits_{k=1}^{n/2}\cos\left[(2k-1)(b+\delta)\beta\right]\frac{\sin b\beta}{\beta}\cos\zeta\beta, & \text{for } n \text{ even;} \\ \frac{2p_0}{\pi}\left(1+\sum\limits_{k=1}^{(n-1)/2}\cos[2k(b+\delta)\beta]\right)\frac{\sin b\beta}{\beta}\cos\zeta\beta, & \text{for } n \text{ odd.} \end{cases} \tag{7}$$

Boundary conditions (3a, b) will be rewritten in the form

$$\sigma_r(\zeta)|_{\rho=1} = \begin{cases} \frac{4p_0}{\pi} \int\limits_0^\infty \sum\limits_{k=1}^{n/2} \cos[(2k-1)(b+\delta)\beta] \frac{\sin}{\beta}\beta \cos(\zeta\beta)\, d\beta, & \text{for } n \text{ even;} \\ \frac{2p_0}{\pi} \int\limits_0^\infty 1 + \sum\limits_{k=1}^{(n-1)/2} \cos[2k(b+\delta)\beta]\beta \frac{\sin}{b}\beta \cos(\zeta\beta)\, d\beta, & \text{for } n \text{ odd.} \end{cases} \tag{8}$$

Substituting the boundary conditions (4), (8) into the general solution (6) at $r = 1$, we obtain a system from which we will find the constants C_2, D_2

$$C_2 = \frac{p_0 r_0}{\pi G} \frac{K_1(\beta)}{\psi(\beta)}, \quad D_2 = -\frac{p_0 r_0}{\pi G} \frac{K_0(\beta) + 2(1-\nu)K_1(\beta)}{\beta\psi(\beta)} \tag{9}$$

where $\psi(\beta) = (2(1-\nu) + \beta^2)K_1^2(\beta) - \beta^2 K_0^2(\beta)$.

Finally, the expressions for stresses will have the form

$$\sigma_r = -\frac{2p_0}{\pi} \int\limits_0^\infty \left[\left((3-2\nu)K_0(\beta\rho) + \left(4(1-\nu)\frac{1}{\beta\rho} + \beta\rho \right) K_1(\beta\rho) \right) C + \left(\beta K_0(\beta\rho) + \frac{1}{\rho} K_1(\beta\rho) \right) D \right] P(\beta) \sin(\beta b) \cos(\beta\zeta) d\beta,$$

$$\sigma_z = \frac{2p_0}{\pi} \int\limits_0^\infty \left[(\beta\rho K_1(\beta\rho) - 2\nu K_0(\beta\rho))\, C + \beta K_0(\beta\rho) D \right] P(\beta) \sin(\beta b) \cos(\beta\zeta) d\beta,$$

$$\sigma_\phi = \frac{2p_0}{\pi} \int\limits_0^\infty \left[\left((1-2\nu)\frac{\rho}{\beta} K_0(\beta\rho) + 4(1-\nu)\frac{1}{\beta\rho} K_1(\beta\rho) \right) C + \frac{1}{\rho} K_1(\beta\rho) D \right] P(\beta) \sin(\beta b) \cos(\beta\zeta) d\beta,$$

$$\tau_{rz} = -\frac{2p_0}{\pi} \int\limits_0^\infty \left[(\beta\rho K_0(\beta\rho) + 2(1-\nu)K_1(\beta\rho))\, C + \beta K_1(\beta\rho) D \right] P(\beta) \sin(\beta b) \sin(\beta\zeta) d\beta$$

where the function $P(b)$ is determined by formula (8), and the constants C, D are given by the relations

$$C = \frac{\pi G}{p_0 r_0} C_2, \quad D = \frac{\pi G}{p_0 r_0} D_2$$

Figure figure 2 (a, b, c) shows the axial stresses distribution for three consecutive chambers.

Analysis of the obtained solutions shows that the presence of several successively located chambers reduces compressive stresses around the cavity and simultaneously leads to a significant increase in tensile stresses between them.

Thus, the results of scientific and industrial experiments and the solution of the analytical problem of stress distribution around one or several successively located cavities allow to formulate the following.

1 When applying the hydrodynamic destruction mode in the near-borehole zone of a coal-gas massif, both due to partial extraction of coal and the development of cracking, many cavities are formed. The sequence of their development and location in space is determined by the nature and intensity of the pressure gradient (destruction) manifestation of the reverse impulse. As a result of a decrease in compressive stresses and an increase in tensile stresses, a complex stress-strain state is formed around the cavities in the massif. An additional

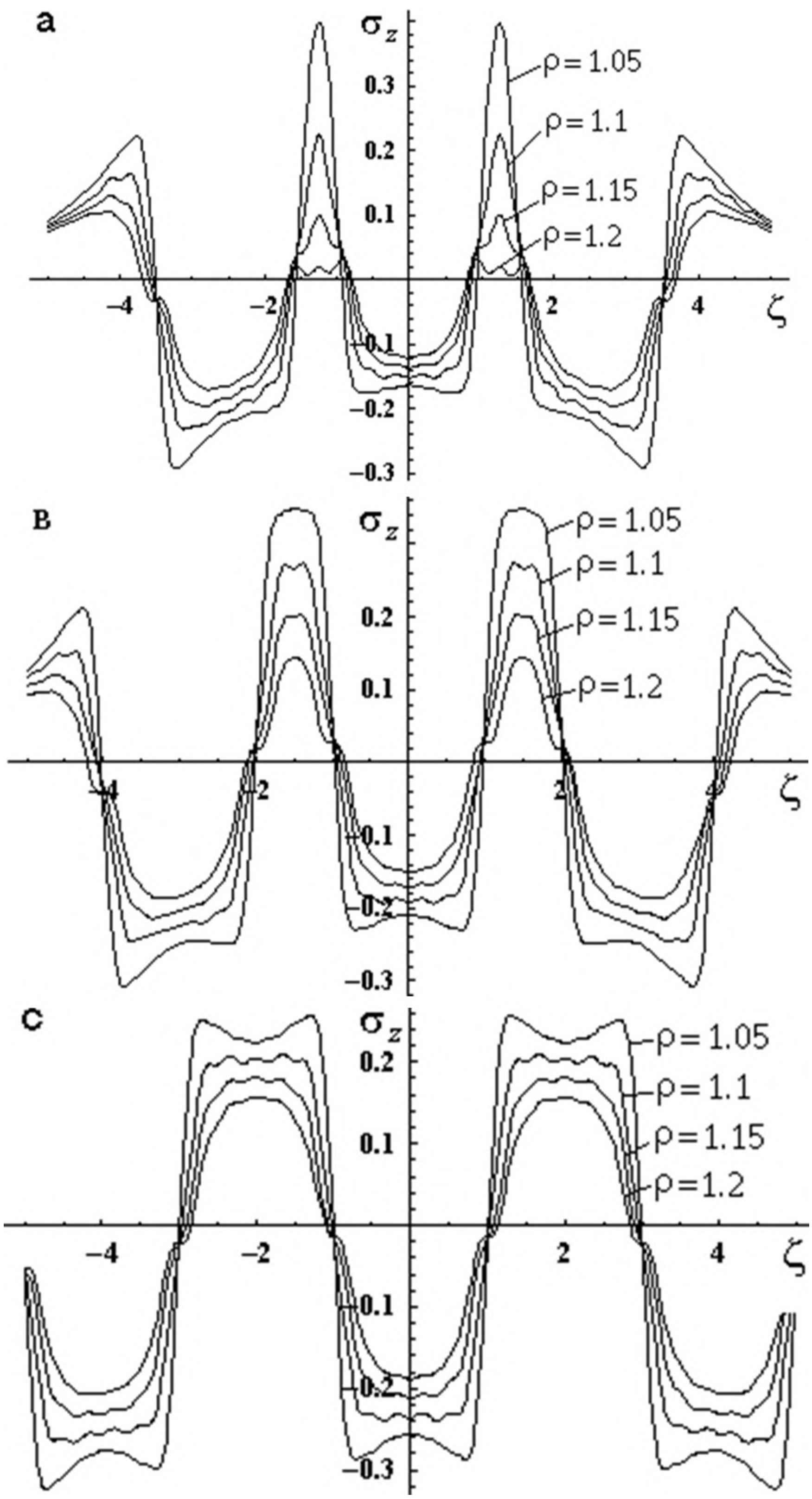

Figure 2. Distribution of axial stresses around the chambers.

increase in stress gradients provokes self-destruction of the massif, which is supported by the transition to the next stage of the HDI mode.

2 The discrete mode of hydrodynamic destruction leads to the intensive formation and development of new open surfaces (cavities), which is a fundamental factor in the intensification of the desorption process during the man-made methane generation by coal-gas medium.

4.3. Dynamic problem solution

Determine the components of the stress state of an elastic medium under the action of a variable internal load. Its peculiarity was the wide use of inertial forces for the dynamic unloading of stressed gas-filled media. The purpose of the approach was to promote development of cracking and degassing in medium. The dynamic parameters of the process of elastic deformation of the medium were determined from the solution of the wave equation in the one-dimensional formulation:

$$r^2 \frac{\partial^2 u_r}{\partial r^2} + r \frac{\partial u_r}{\partial r} - u_r = \frac{r^2}{\nu_p^2} \frac{\partial^2 u_r}{\partial r^2} \tag{10}$$

where u_r (r, t) – radial displacement of an elastic medium, m; t – time of the deformation process, s; ν_p – elastic wave velocity, m/sec.

Boundary conditions on the inner and outer surfaces of the borehole were determined as

$$\sigma_r \Big|_{r=r_0} = -\psi(t); \quad \sigma_r \Big|_{r=r_N} = 0 \tag{11}$$

where r_0 – inner radius; r_N – outer radius.

Despite the large number of options for solving this equation, no simple solutions have yet been found. The found solutions are complex in form and can be obtained using complex numerical algorithms.

The solution given in [17] directly uses widely approved integration methods. For the case of plane strain, the radial σ_r and annular σ_θ stresses can be calculated using formulas (12), (13).

Using the direct Fourier transform in time t to equations (10), (11), we obtain a second-order ordinary differential equation with respect to the displacement transform $\overline{u}_r$ and the transformation parameter ω, which is a Bessel equation, whose general solution is known:

$$r^2 \frac{d^2 \overline{u}_r}{dr^2} + r \frac{d\overline{u}_r}{dr} + \left(\frac{r^2}{\nu_p^2} \omega^2 - 1 \right) \overline{u}_r = 0 \tag{12}$$

$$\overline{\sigma}_r|_{r=r_0} = -\overline{\psi}(\omega), \quad \overline{\sigma}_r|_{r=r_N} = 0 \tag{13}$$

$$\bar{u}_r = A \cdot J_1 \left(\frac{\omega \cdot r}{\nu_p} \right) + B \cdot Y_1 \left(\frac{\omega \cdot r}{\nu_p} \right) \tag{14}$$

where $A(\omega)$, $B(\omega)$ – arbitrary constants determined from the boundary conditions (12); ω – transformation parameter, 1/s; ν – Poisson's ratio; J_1, Y_1 – Bessel functions of the first and second order; $\overline{u}_r$ – displacement transform, m; $\overline{\psi}(\omega)$ – load transform; $\overline{\sigma}_r$ – transform of radial stresses, Pa.

Using the formulas for the case of plane strain for radial and tangential stresses in displacements and using the direct integral Fourier transform in time, we obtain:

$$\overline{\sigma}_r = \frac{E}{1-\nu^2} \left(\frac{d\bar{u}_r}{dr} + \nu \frac{\bar{u}_r}{r} \right); \quad \overline{\sigma}_\theta = \frac{E}{1-\nu^2} \left(\frac{\bar{u}_r}{r} + \nu \frac{d\bar{u}_r}{dr} \right) \tag{15}$$

where E – modulus of elasticity, Pa; $\overline{\sigma}_\theta$ – transform of tangential stresses, Pa.

Substituting the expression for the transform of displacements (13) into equation (14) and using the formulas for differentiating Bessel functions of the first and second order, we obtain the following formulas for transforms of radial and tangential stresses, taking into account the notations $\xi = \omega \cdot r_0/\nu_p$:

$$\frac{\overline{\sigma}_r}{2G} = A\left(\frac{1}{1-\nu}\frac{\xi}{r_0}J_0\left(\frac{\xi r}{r_0}\right) - \frac{1}{r}J_1\left(\frac{\xi r}{r_0}\right)\right) + B\left(\frac{1}{1-\nu}\frac{\xi}{r_0}Y_0\left(\frac{\xi r}{r_0}\right) - \frac{1}{r}Y_1\left(\frac{\xi r}{r_0}\right)\right) \tag{16}$$

$$\frac{\overline{\sigma}_\theta}{2G} = A\left(\frac{\nu}{1-\nu}\frac{\xi}{r_0}J_0\left(\frac{\xi r}{r_0}\right) + \frac{1}{r}J_1\left(\frac{\xi r}{r_0}\right)\right) + B\left(\frac{\nu}{1-\nu}\frac{\xi}{r_0}Y_0\left(\frac{\xi r}{r_0}\right) + \frac{1}{r}Y_1\left(\frac{\xi r}{r_0}\right)\right) \tag{17}$$

where J_0, Y_0 – Bessel functions of the first and second type of zero order; G – displacement modulus, Pa; $\bar{t} = v_p t/r_0$ – dimensionless process time; r – current radius; $t_c = t_2 - t_1$– valid load rejection time, s; q_0 – internal load, Pa; t_1, t_2 – respectively, the time of increase and the time of load rejection, counting from the origin of the coordinates, sec.

As can be seen (16), (17), the initial expressions for determining stresses and displacements are cumbersome and inconvenient for practical use.

The main parameters influencing the process of non-stationary deformation of the elastic medium include: the inner radius of the borehole r_0, the magnitude of the load on the inner surface q_0, the elastic wave velocity v_p and the time of the internal load rejection t_c. Estimating the degree of influence of each parameter is not a simple task, since they are under the integral. From a practical point of view, the dependence of the change in the radial tensile stresses occurring on the inner surface of the cylindrical cavity on the above-mentioned parameters is of great interest. Since most methods of stimulating the destruction of gas-content medium (coal) and degassing are based on the use of inertial forces, we will consider the procedure for obtaining these dependencies in the area of their action. The graphical dependences of stress (displacement) changes in time after the end of the force action have the form of a damped sinusoid. All calculations and transformations are determined in relation to the maximum value of the radial tensile stresses in the first half-wave of stress change in the area of inertial forces action (figure 3).

The presented solutions to problems (16) and (17) in the form of simple engineering formulas convenient for calculating stresses or displacements of an elastic medium during short-term unloading using the method of successive approximation are given in [17].

As a representation function, we will take the value of the maximum tensile stress in the first half-wave of its change related to the value of the maximum amplitude of the internal load q_0 :

$$\bar{\sigma}_r = \frac{\sigma_r}{q_0} = \sigma(t_c^{\alpha_1} \cdot \upsilon_p^{\alpha_2} \cdot r_0^{\alpha_3}) \tag{18}$$

where α_1, α_2, α_3 – indicators of the functions degree of the parameters under studying. The domain of the function definition is set by the parameters change intervals: the interval of the inner radius change of the cylindrical cavity r_0 = 0.05-0.5 m; elastic wave velocity υ_p = 100-2000 m/sec.; load rejection time t_c = 0.001-0.1 sec.

Reference point $M{=}M(x_1^0, x_2^0, ..., x_n^0)$ $M \in \overline{D}$ is set by the values of the parameters: load rejection time t_1^0= 0.01 sec.; elastic wave velocity υ_p^0 = 600 m/sec.; inner radius $r_0^0 = 0.1$ m.

Using the stages of the sequential approximation method algorithm, we obtained:

$$\sigma_r = 0.917\frac{q_0^{1.0} \cdot r_0^{1.01}}{\upsilon_p^{0.957} \cdot t_c^{0.944}} \tag{19}$$

Taking into account the closeness of the exponents parameters to unity, we will obtain a more convenient formula for calculating the tensile stresses on the inner contour of the cylindrical cavity at the first half-wave of the stress change in the form:

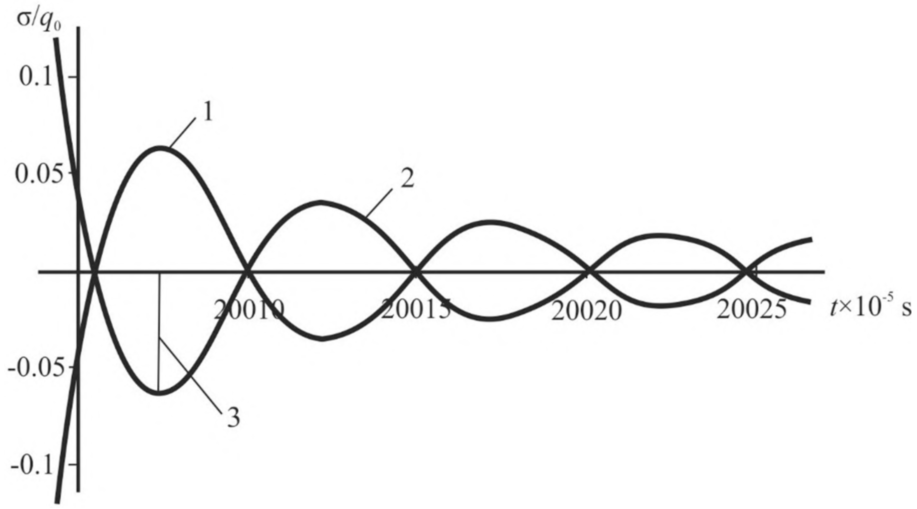

Figure 3. Change of radial and annular stresses with time in the area of inertial forces action at u_p = 400 m/sec.; t_c = 0.001 sec.; $r = r_0$ = 0.1 m; r_N = 1000 m. 1 – annular dimensionless stresses; 2 – radial dimensionless stresses; 3 – maximum radial tensile stresses in the first half-wave.

$$\sigma_r = 0.9\frac{q_0 \cdot r_0}{\upsilon_p \cdot t_c} \tag{20}$$

A comparison of the relative stress errors determined by formulas (19) and (20) was made with the exact one obtained by the Fourier integral transformation method. The analysis of solution errors (19) showed: the average error for the load rejection time does not exceed 3.8%, for the velocity of the elastic wave – 2.0%, for the inner radius – 4.3%.

The analysis of the results of comparing the relative errors of the stresses calculated by formula (20) with the exact one obtained by the method of integral Fourier transformation showed that the average relative error for the load rejection time does not exceed 2.7%, for the velocity of the elastic wave – 2.2%, and for the inner radius – 4%.

Regarding to the usefulness of formula (20) for regulating the rock layer that will separate from the massif under the tensile stresses action, it can be argued that for different types of rocks the rate of load rejection should be correspondingly different. Reducing the rejection time can significantly increase the tensile stress and, accordingly, increase the layer of rocks that will be separated. The risk of reducing the power of the layer that separates is associated with a decrease in the load on the cavity walls or an increase in the time of its discharge.

5. Conclusion

1 Hydrodynamic impact on the coal and gas massif through boreholes with a diameter of 0.1 m due to partial extraction of coal up to 7% of the volume of the treatment zone; cracking and degassing, leads to the formation of many open defects in the form of cavities. The sequence of their development and location in space is determined by the nature and intensity of the pressure gradient (destruction) manifestation by the reverse impulse at an elastic wave velocity of 600 m/s. As a result of a decrease in compressive stresses and an increase in tensile stresses, a complex stress-strain state is formed around the cavities. An additional increase in the stress gradient leads to the development of the process of self-destruction of coal and new formations on its surface. The process of self-destruction

is supported by gas release from the massif and partial extraction of destroyed coal during the change of the pressure set-relief cycle.

2 The discreteness of the hydrodynamic destruction mode leads to the intensive formation and development of new open surfaces (cavities), which is the main factor in the intensification of the desorption process during man-made methane generation by coal medium.

3 The process of self-destruction of coal and its intensity depend on changes in the dynamic components of the process over time. The change of compressive stresses by tensile stresses under the action of variable load and inertial forces leads to the destruction of the coal layer and changes in the stress-strain state of the gas-filled medium. A decrease in pressure relief time leads to an increase in tensile stresses and more effective failure.

4 The average relative error in the calculation of the proposed model parameters calculated by formula (20), for the load rejection time up to 0.1 s does not exceed 2.7 %, for the elastic wave velocity – 2.2 %, and for the internal radius of cylindrical cavities – 4 %.

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The current state and development prospects of the graphite industry of Ukraine

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The current state and development prospects of the graphite industry of Ukraine

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Abstract. The article is devoted to establishing the current state of graphite deposits development in Ukraine and the prospects of supplying industry with this critical raw material. The countries with the largest production of natural graphite and Ukraine's share of the world market have been determined. Global trends in graphite consumption in industry and its impact on market value have been established. The mining and geological conditions of typical graphite deposits occurrence have been determined, which indicates the expediency of surface mining. The geological characteristics of the largest graphite deposits of Ukraine have been studied, which allows further research to determine directions for increasing the efficiency of beneficiation of graphite raw materials and to increase the greening of production. The main areas of graphite use in high-tech sectors of the economy are given, which confirms the critical role of this raw material in the creation of renewable energy chains. Estimated reserves of graphite have been established in the most significant graphite deposits of Ukraine, which include Zavallivske, Petrivske, Troitske, Mariupolske, Balakhivske and Burtynske. The estimated content of graphite in the ore of the main deposits has been determined, which makes it possible to forecast the country's resource availability with this critical raw material in the future.

1. Introduction

Graphite is a critical mineral raw material with a specific set of characteristics that make it optimal and practically unchanged in various fields of industry, production and scientific research. Even without being a metal, it exhibits unique properties as a metal and a non-metal at the same time, having a unique set of characteristics arising from its molecular structure [1]. If at the beginning of graphite mining, it was used mainly for the metallurgical industry, then later the scope of use expanded significantly.

Graphite has been mined in the world for several centuries, and now the main exporters of this material are China, Mexico, Canada, Brazil and Madagascar [2]. At the same time, the largest producer of graphite in the world is China with an average production level of 700,000 tons per year. This country accounts for 65% of world graphite production and 35% of consumption. The second place in terms of development was occupied by India with 170,000 tons and production of graphite in Mozambique in 2019 amounted to 100,000 tons. The fourth place in terms of graphite production is occupied by Brazil with an annual production of 95,000 tons.

In this ranking, Ukraine was ranked 7th with an annual production of 20,000 tons. The most dominant enterprise in Ukraine for the production of this critical raw material is "Zavallivsky

Graphite", the development of which is carried out by the surface mining.

The analysis of information open sources made it possible to establish that world prices for graphite have significantly increased in recent years, and taking into account the projected increase in the production of electric vehicles, the demand for this raw material will increase in the future. The previous sharp increase in price was recorded in 2011-2012, which was associated with significant demand from manufacturers of lithium-ion batteries, but in 2013, prices decreased significantly due to the decline in the development of the Chinese economy and the insufficient development of Western economies [3].

Starting from 2020, there is a sharp increase in the price of natural graphite, which is due to increased demand in the moderate of an increase in the volume of offers. According to open sources of information, from 2020 to 2022, the price of graphite on the world market increased 3 times and reached 2281 $/t [4], which brought it closer to the indicators of 2012 (figure 1).

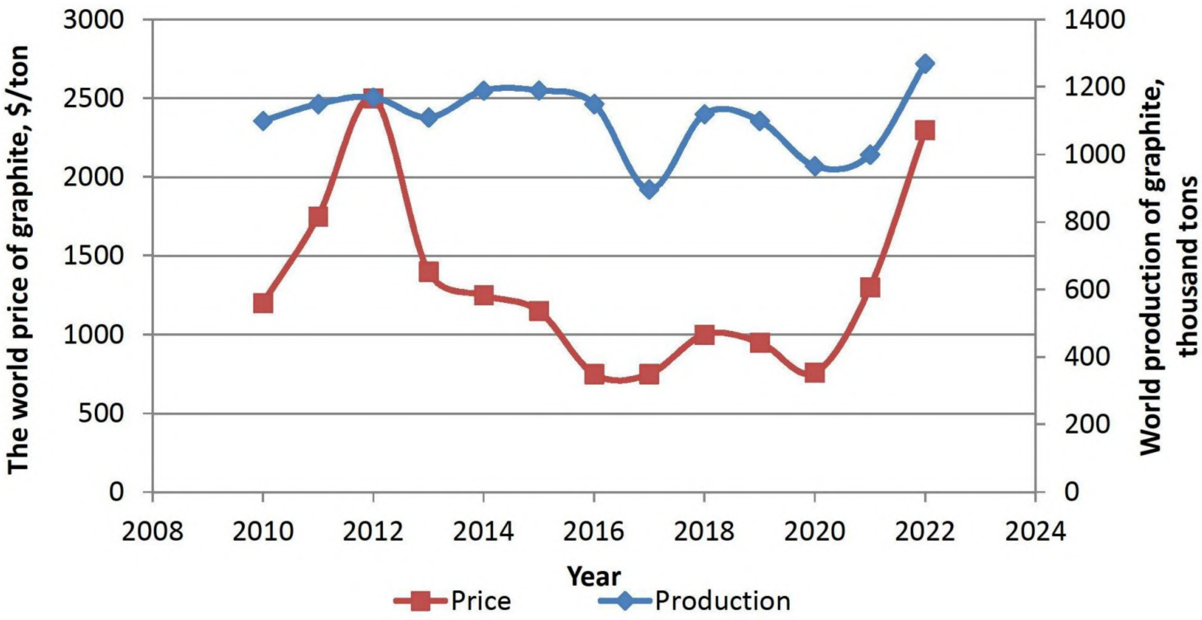

Figure 1. World production and value of graphite in the period 2010-2022.

The indicators displayed on the graph (figure 1) allow establishing that the annual volumes of world graphite production were in the range of 850-1270 thousand tons, and in recent years the value has increased considerably with an insignificant decrease in production volumes.

In connection with the growing global demand for graphite raw materials, determining the state of graphite deposits development of Ukraine and studying the issue of using this critical raw material in various industries are urgent scientific and practical tasks.

The aim of the research is the analysis of technological schemes for the mining and extraction of graphite in Ukraine to meet the needs of the industry of the European Union with critical raw materials.

To achieve the goal, the following research tasks should be solved: analyze the mining and geological conditions of graphite deposits in Ukraine; to investigate the directions of using graphite for high-tech production processes; to establish approximate reserves of graphite raw materials in the most promising deposits of the country.

2. Analysis of mining and geological conditions of graphite deposits

Ukraine has important deposits of graphite, confined to the Ukrainian crystalline shield with a content of valuable components of 2.5 – 20%. In general, there are four graphite-bearing regions in the country: Berdychiv, Priazovsky, Kryvorizky, Pobuzky, where there are approximately 100 deposits and zones with crystalline graphite, which genetically belong to the metamorphic type [5]. Graphite is found in places of contact between hard coal and igneous rocks, in crystalline slates and marbles. It is also found in the form of inclusions of acidic, medium and basic igneous rocks with limestones.

There are 6 graphite deposits on the state balance of mineral reserves (figure 2). One of the main ones is the Zavallivske deposit, which is located on the left bank of the South Bug River and is the largest in Europe with confirmed graphite reserves of 96.6 million tons (6.1 million tons of ordinary graphite).

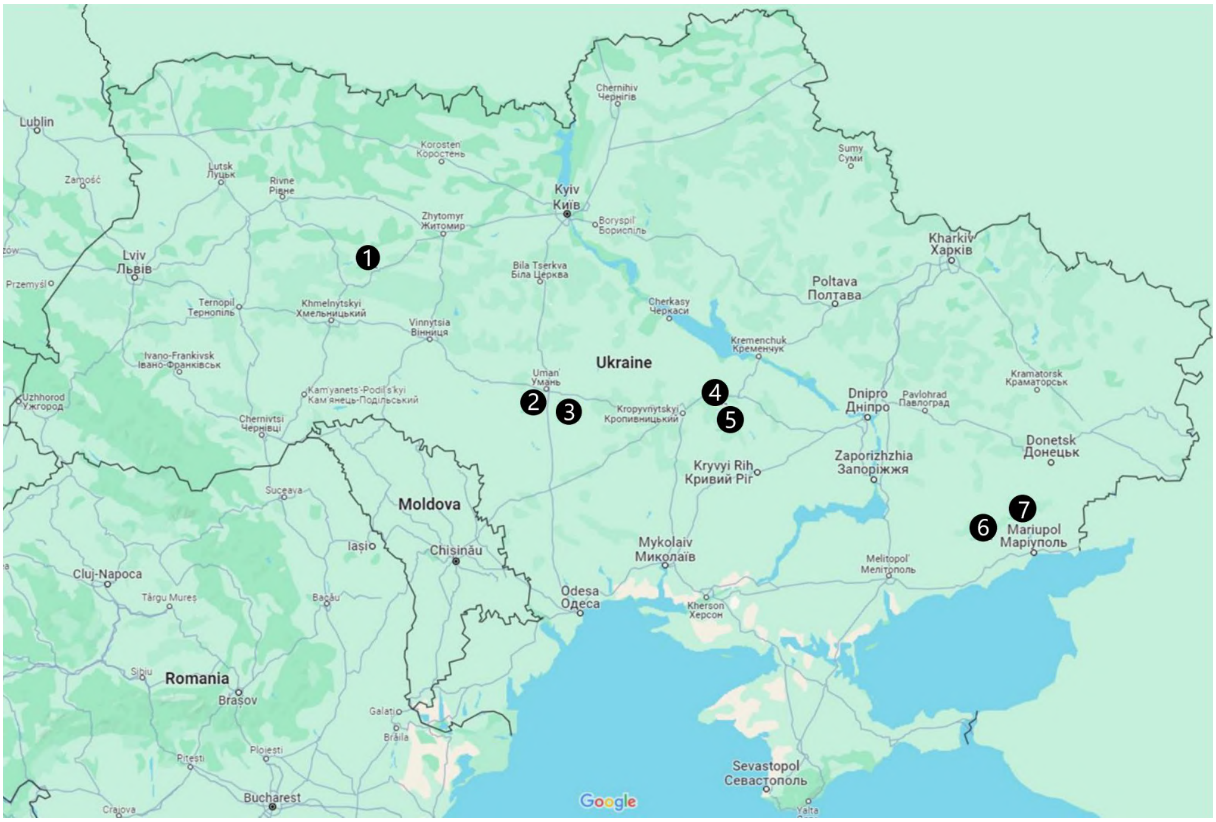

Figure 2. Map of the graphite ore deposits location (Data according to the annual publication of State research and production enterprise "GeoInform of Ukraine" for 2021): 1 – Burtynske; 2 – Zavallivske; 3 – Zarichna; 4 – Balakhivske; 5 – Petrivske; 6 – Troitske; 7 – Mariupolske.

The Zavallivske deposit is located in the fault zone that separates the northern and southern blocks. The northern block is composed of rocks of the Gaivron complex (enderbites), and the southern block is composed of the Khashuvato-Zavalliv rocks of the Buzka series (marbles, calciphyres, magnesian skarns), between the blocks there is an intensely dislocated stratum of graphite-containing crystalline schists and gneisses. This zone of intensely dislocated rocks determines the morphology, structure and mineral composition of ores and graphite is in paragenesis with pyrrhotite and magnetite. Zoning in the distribution of pyrrhotite and magnetite in the central zone was also established, indicating the presence of a geochemical barrier between the blocks. According to the research results, graphite on this barrier was formed as a result of mixing two fluids of different composition.

Recently, two promising deposits of Balakhivske (Kirovohrad region) and Burtynske (Khmelnytska region) have been explored, which are not low-grade to Zavallivske in terms of quality characteristics, so they can become a raw material base for the creation of new mining enterprises.

Graphite is distinguished by its structure – flaky, dense-crystalline and hidden-crystalline types, there are also corresponding grades depending on the use.

Of greatest interest are ores containing flake graphite, where it is placed in the form of individual crystals that form flakes up to several millimetres in size. Coarse-flaky (for example, Madagascar, India), medium-flaky and fine-flaky (Germany) graphites are distinguished by the size of the scales and morphological features. At the same time, the amount of graphite flakes is not constant within one deposit, it depends on the type of host rock. For example, coarse-luxated graphite is found mainly in the Zavallivskyi, Velikovodyanskyi, Bebenkivskyi deposits, and medium-flaky graphite – in the White Horby, Volyanskyi, Starokrymskyi, and Troitskyi deposits. Other known deposits of graphite are classified as fine-flaky type [6].

Quite often, for example, in the Zavallivske and Bebenkivske deposits, separate veins and strips of amorphous graphite are found in cracks. This graphite is a secondary formation that arose as a result of the destruction and removal of graphite flakes in cracks. The occurrence of graphite in the form of separate and equal-sized scales and its clusters forms graphite ore. With contents that meet the condition standards, such ore has industrial value, but these are separate values for each deposit.

Six types of graphite ores are distinguished in the Ukrainian graphite deposits. Four of them are of no industrial importance and are represented by scattered individual fine flakes, liquid accumulation of graphite of various sizes in the form of bushes and nests, dense uniform saturation of rocks with graphite flakes, and accumulation of amorphous graphite. The fifth type in the form of continuous accumulations of graphite flakes of different sizes in the form of lenses, veins and veins (Zavallivske, Starokrymske, Bebenkivske deposits) already forms industrial reserves. The sixth type of graphite ores is industrial and is represented by a dense uniform saturation of rocks with an accumulation of scales in the form of nests and bushes (Zavallivske, Troitske, Starokrymske deposits, etc.). This type, unlike the rest, is well enriched.

Considering the above, four significant deposits of graphite can be distinguished in Ukraine: Zavallivske, Petrivske, Burtynske and Starokrymske deposits. Zavallivske represents a single raw material base for the production of graphite. The Balakhivske field in the Kirovohrad region is promising, the reserves of the license area of which up to a depth of 150 m amounted to 43 million tons, the total reserves are 185 million tons, and the estimated resources are 500 million tons.

The depth of graphite ores mainly ranges from 10 to 80 meters. Graphite-bearing rocks form layered and lenticular structures up to 300 m thick and 500 to 1500 m long, sometimes reaching 3.5 to 5.0 km. Graphite is characterized by flaking and is found in ores in amounts from 2.5 to 20%, rarely up to 30%. Estimated reserves of graphite ore in Ukraine amount to approximately 230 million tons. There is also the potential to increase these reserves by another 100 million tons [7].

Most deposits of Ukraine are characterized by a layered form of graphite ore occurrence in the form of elongated bands, the length of which is several times greater than the width. The saturation of these bands with graphite is uniform and maintained along the extension. The layered type refers exclusively to gneiss rocks. There are also cases when the graphite-bearing strip consists of several types of graphite-bearing rocks, separated by layers of empty or low-productivity rocks, which complicates further mining (common in the Azov region, less so in Kryvorizha and Pobuzhha) [6, 7].

In addition to layered deposits, forms of occurrence in the form of lenses, xenoliths, inclusions, nests and inclusions have been recorded, but they do not form industrial reserves. Vein forms of graphite deposits are also present in separate areas of many graphite deposits. It is also worth noting that of all the listed deposits, only strata deposits are of industrial importance.

3. Use of graphite in high-tech production processes

Today, graphite is necessary for the production of lithium-ion batteries, diamonds, composite and lubricating materials of various types, fuel cells, nanotechnologies and many other renewable energy technologies. The main attention in the world today is given to it because it is a critical material in the manufacture of lithium-ion batteries. Despite its considerable geographical distribution, preference is given to raw materials with a minimum content of impurities obtained by synthesizing petroleum coke. Since the development of modern technology is highly dependent on the supply of this raw material, EU countries are making a lot of efforts to diversify the supply of graphite materials.

Significant demand for graphite in the world has recently been increasing, as it is a critical raw material in the production of lithium-ion batteries for electric vehicles. The rapid development of this market requires large volumes of attraction of natural graphite [2]. For example, up to 54 kg of graphite must be used to make one Tesla S electric vehicle.

The study of possible directions for the use of graphite in high-tech production processes also made it possible to establish a wide range of its use. Among the most common final goods, graphite is used in the production of lithium-ion batteries, carbon steel, crucibles, friction and lubricants, pencils, insulation and composites, flame retardants, seals and foils, refractory materials (figure 3). It is also used as a recarbonizer, fuel cell and metal forming [8].

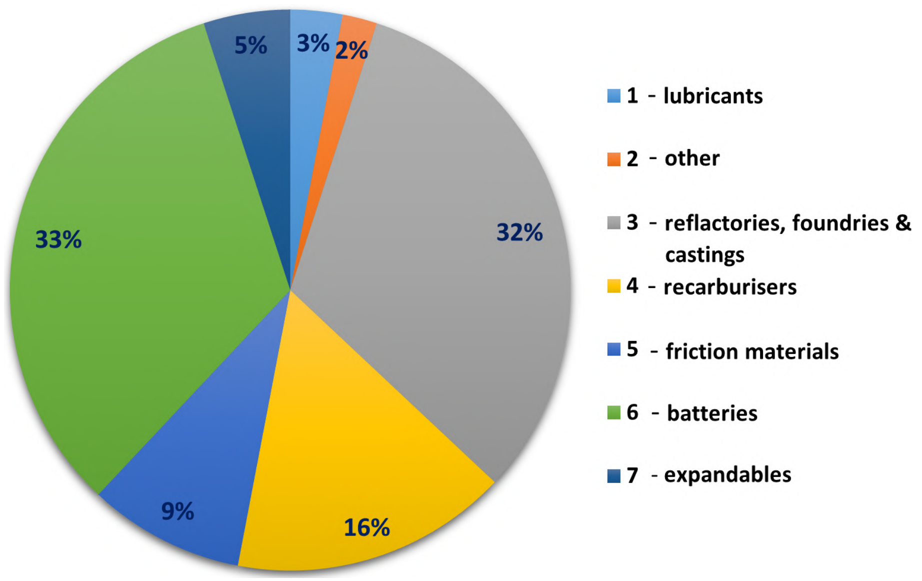

Figure 3. Natural graphite demand by application as of 2022.

One of the main areas of graphite consumption in world industry is the metallurgical industry. Due to its high heat resistance (in an oxygen-free environment) and chemical resistance to molten metals, graphite is used for the manufacture of melting crucibles and lining plates.

Natural and synthetic graphite are increasingly used as anode materials in the production of battery electrodes. This is possible due to their high electrical conductivity and chemical resistance to almost any aggressive aqueous solutions, even higher than that of noble metals [9].

Graphite is also widely used as a tool for processing casting molds. This is a water-based paint that contains amorphous or finely dispersed flaky graphite. After applying this paint to the inner surface of the mold and drying, a thin graphite layer is created. This layer makes it easier to separate the cast object after the hot metal has cooled. Graphite lubricants are used in conditions of high and low temperatures: for lubrication of dies during forging, as anti-seize lubricants, and also for lubrication of gears of mining equipment.

In Ukraine, extraction and beneficiation of graphite ores is mainly carried out at the Zavallivske graphite plant. The company produces grades of graphite for various sectors of industry, such as crucible, elemental, foundry, electric coal, battery, pencil, friction metal-ceramic, powder, special low-ash and others. The main products are foundry, crucible and elemental graphite. Production of graphite products by Ukrainian enterprises meets world quality standards and is exported to other EU countries [5].

4. Development of graphite deposits in Ukraine

The dynamics of natural graphite production in Ukraine shows its significant influence in terms of supply to EU countries. So, in 2020, 5.2 thousand tons of graphite were produced, which was about 0.5% of world production. It should be noted that according to the annual report on the evaluation of critical raw materials, graphite is not only a critical, but also a strategic raw material [9]. The development of graphite deposits has certain difficulties, which is due, first of all, to economic reasons. The main deposits of Ukraine with a high level of graphite reserves include: Zavallivske, Petrivske, Troitske, Mariupolske, Balakhivske and Burtynske (figure 4).

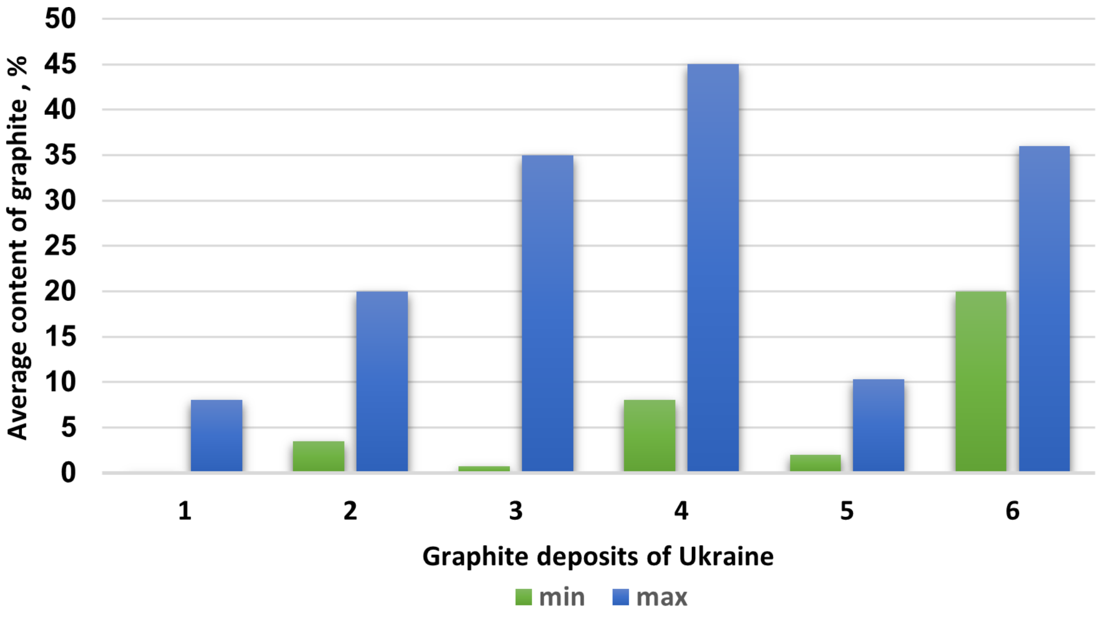

Figure 4. The average content of graphite in ore by deposits : 1 – Troitske; 2 – Petrivske; 3 – Mariupolske; 4 – Zavallivske; 5 – Balakhivske; 6 – Burtynske.

Pobuzky ore district the most attention a graphite-bearing area composed of igneous and to a lesser extent, metamorphic rocks of the Archaean age. This area includes the Zavallivske deposit, which is unique in its size and structure.

This deposit is the largest in Europe and the second in the world. Extraction is carried out by surface mining method [10] using well charges and hydromechanization [11]. The deposit's ores are enriched by flotation (and chemical methods), resulting in a concentrate that contains high-quality graphite in the amount of 85 to 99.5% and has an ash content of no more than 10-15%.

The deposit belongs to the stratimorphic type, where the formation of graphite is characterized by metamorphic or organogenic-syngenetic hypotheses [6]. The high industrial ores value of the Zavallivske deposit allows for the production of a wide range of graphite commercial grades, among which the most valuable is crucible graphite. A number of sulphide and oxide minerals were found in the rocks of graphite deposit, which may also provide grounds for a more thorough study of the genesis, taking into account the changing views on the deposits formation in the world. A good example is the deposits of the USA (Black Hills) or Sri Lanka, which were previously considered metamorphosed, but now hydrothermal in origin.

Graphite mining is carried out only in the south-eastern part of Zavallivske deposit by a surface mining [12] of critical raw materials. The depth of the pit reaches 250 m. The design capacity of the beneficiation plant is 800,000 tons/year of ore, and the design term of operation is 110 years. The products are exported to the countries of the European Union, Asia, the USA, etc.

The Petrivskoe deposit is also typical, where graphite is mainly found in the lower parts of the metamorphosed layer of rocks. It can occur as small clusters and plates in crystalline limestones, graphitic quartzites and gneisses. A significant amount of graphite is found in graphite shales, but they cannot be used as an ore for mining because they are not suitable for beneficiation. Biotite-plagioclase gneisses contain more crystalline graphite, where its concentrations increase with depth. Also, graphite rocks directly, in most cases, do not form a continuous ore body. The presence of migmatized of diopside hornblendes and graphite-coal slates, along the graphite contours near the pegmatite veins, indicates the genesis of the deposit through metamorphic processes and assimilation of limestones by granites [6].

The Balakhivske deposit of the Kirovohrad region with estimated resources of 500 million tons is also promising for development. The reserves of the license area of which up to a depth of 150 m amounted to 43 million tons, and the total reserves – 185 million tons.

Based on the analysis of the study [13], it was established that the deposits of graphite deposits of Ukraine belong to category B, that is, the reserves of mineral raw materials are explored, but mined in limited quantities. The dynamics of the extraction of this raw material in the countries of the world has been established, which shows that countries with smaller reserves extract significant volumes of graphite. While countries with large reserves extract this critical raw material in minimal volumes. This indicates the different economic importance of graphite raw materials for each region separately.

5. Conclusions

It was determined that since 2020, the world market has a sharp increase in the price of natural graphite, which is due to the moderate of an increase in the offers volume. According to open sources of information, from 2020 to 2022, the price of graphite on the world market increased 3 times and reached 2,281 $/t with moderate growth indicators of the global production of this raw material from 850 to 1,270 thousand tons.

It has been established that Ukraine has a high level of resource provision with graphite, a critical raw material, which allows it to become a reliable supplier to the countries of the European Union. In addition, the establishment of graphite exports will lead to the development of the goods production with added value. For this, it is necessary to consider the prospects of expanding the raw material base of graphite by conducting research involving areas with a high content of this critical raw material in ore.

The conducted research made it possible to establish the main characteristics of the graphite deposits of Ukraine, including the capacity of the ore deposit, the complexity group of the geological structure, the average content of graphite in the ore, the amount of reserves, etc. It was determined that the highest average content of graphite in the ore is observed in the Zavallivske deposit and varies from 8 to 45%, while the lowest concentration is observed in the

Troitske deposit, where the graphite content in the ore does not exceed 8%.

The most promising direction of further research is technological solutions for modernization of production and improvement of environmental protection of the processes at the existing Zavallivske graphite plant, which will allow to expand the existing list of commercial products, for example, electro carbon graphite for use in the manufacture of lithium-ion batteries.

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About the methodology to improve concept of maximum security of nuclear facility at minimum costs

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About the methodology to improve concept of maximum security of nuclear facility at minimum costs

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Abstract. Given work describe proposals concerning Pampuro method use for improvement of the maximum security concept of nuclear facility at minimum costs. The main provisions of the maximum security concept ensuring for nuclear facility at minimum cost are analyzed. The meaning of the terms threat and risk in relation to critical infrastructure objects is considered. One of the directions for optimal management concept implementing of protected critical infrastructure object using the Pampuro method is proposed. The mathematical model was developed to ensure security of protected nuclear facility at minimum of costs. It takes into account different intensities of terrorist influence. It was concluded that software implementation of the developed mathematical apparatus can be used as a unified software product by security services or physical protection services of various protected objects.

1. Introduction

State's ability to ensure security and protection of critical infrastructure objects from terrorist influence [1–3] is one of the key factors determining the independence of the state. It includes nuclear power plants (NPP), plants on uranium ore enrichment, factories for production and storage of nuclear fuel. They are strategic nuclear facilities [4, 5]. Security management of these protected objects is an urgent problem [6]. Traditionally, its solution is carried out using the concept of deep echelon protection. It is based on an expert approach to ensure security of NPP [7] and international regulations on NPP safety [8–11]. This concept is reduced to security due to creation of protection system from physical barriers. They are built according to the principle of preventing all possible catastrophic events and in their occurrence case – minimizing possible consequences. Engineering and organizational measures are used to create barriers. They should provide at least five levels (barriers) of protection.

NPP safety methods were developed based on the concept of deeply echeloned protection. Some of them are described in works [12–14]. However, these methods do not allow optimal security management – they are associated with methodological limitations of the concept of deeply echeloned protection.

Methodologically important case requires accounting for unlikely events such as an earthquake or a plane crash. For example, periodicity of an earthquake is assumed to be equal one in 10^6 years. It is not possible to assert constancy of the earthquake frequency over a limited interval τ if the service life of the object $\tau \ll 10^6$ years (for NPP $\tau \ll 100$ years). In other words, such cases should be considered as statistically unstable in relation to the accident case at potentially dangerous object and in particular at nuclear power plant. Thus, consequence of the methodological error of postulating probabilistic essence of potentially possible serious accidents (such as the melting of the active zone) is transfer of hypothetically possible accidents to the category of statistically regular and therefore theoretically inevitable. Then the deep defense concept becomes theoretically futile because an accident is inevitable with any defenses according to the probabilistic hypothesis.

The work aim is to consider proposals for the Pampuro method use to implement improvement of maximum security concept of nuclear facility at minimum costs. It is necessary to consistently solve number of tasks to achieve the set aim:

(i) analyze the basic provisions of the ensuring maximum security concept of nuclear facility at minimum costs;
(ii) consider meaning of the terms “threat” and “risk” in relation to critical infrastructure objects;
(iii) propose one of the directions of the concept improvement of optimal management of the protected critical infrastructure facility using the Pampuro method.

2. Basic provisions of maximum security ensuring concept of nuclear facility at minimum costs

Optimal security management of the protected object (maximum effect at minimum costs) is the main principle of optimal security management. At the same time security of protected nuclear strategic object should be considered as a combination of all types of security and physical protection of the object. They are defined as degree of its stability and ability to resist threats. A “thret” is a potentially possible case, action, process or phenomenon that can lead to harm. For nuclear strategic object it is ability to resist military, terrorist, political, social, legal and organizational threats. This is ability to counteract man-made and informational, environmental and criminal threats caused by the action of the forces of nature. Ensuring maximum security is achieved through its practical implementation. At the same time implementation should be carried out with the maximum possible economic efficiency, with minimum amount of all security costs and their optimal distribution [15, 16].

Essence of the optimal security management concept of protected nuclear strategic facility is to ensure maximum security of nuclear facility at minimum costs. It is shown in figure 1 [17].

The abscissa axis shows the risk value R. It determines probability of catastrophic event. Accordingly, it is measured as a fractional number or as a percentage. It cannot exceed a maximum value equal to one or 100%. The value indicators of C calculated in hryvnias or conventional units (usually in thousands or millions of value units) are plotted along the ordinate axis.

The diagram shows cost curves for two technologies implemented at nuclear facility. The first is costs for preventing a hypothetical catastrophic case. Higher costs lead to the lower risk of catastrophic event and vice versa. The second is costs of the consequences eliminating of hypothetical catastrophic case. In some cases, this technology is called insurance costs. Here, the higher risk leads to the higher costs. The third curve shows the total costs of both technologies. The situation determined by the point of intersection of the first and second curves is the

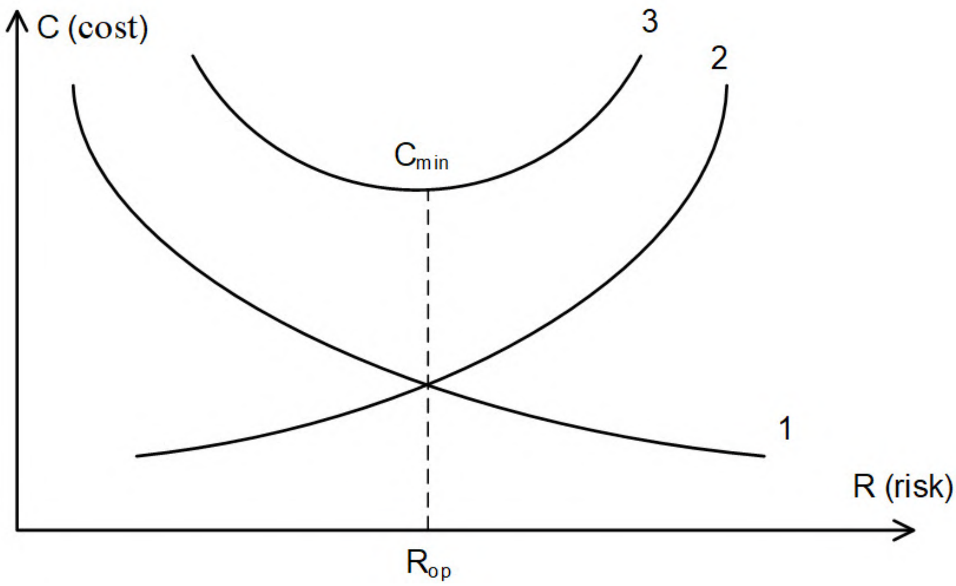

Figure 1. Dependence of security costs on the risk of catastrophic event: 1 – Costs for preventing a hypothetical catastrophic case; 2 – Costs of the consequences eliminating of hypothetical catastrophic case; 3 – Total costs of both technologies.

situation of optimal security management of protected nuclear facility. Under this situation, the optimal (acceptable) value of the occurrence risk of the hypothetical catastrophic case is ensured. It requires minimal total costs.

The concept itself is based on the following eight postulates [17]:

1) optimal security management of the protected object (maximum effect at minimum costs);
2) possibility of occurrence of any hypothetical (virtual) catastrophic case, both at the protected object and in its immediate vicinity;
3) need to use all possible technical means, technologies, laws and knowledge to prevent occurrence of hypothetical catastrophic cases at the protected object and in its immediate vicinity;
4) presence of margin of security control of the protected object;
5) determination of the upper limits of development of hypothetical catastrophe which can cause loss of control both for protected object security and the object itself (its main technological cycle);
6) prediction of options for extreme management of protected object when the upper limits of the development of hypothetical catastrophe is occured;
7) calculation of the total costs for security ensuring of the protected object;
8) compliance with the system in managing protected object and ensuring its safety.

Their practical implementation faces two key concepts – “threat” and “risk” despite the apparent simplicity of the stated principles.

3. Meaning of the terms “threat” and “risk” in relation to critical infrastructure objects

A threat is an opportunity. In turn, opportunity is a direction of development available in every phenomenon of our life. It acts as a future and as an explanation. It has a categorical nature from a philosophical point of view. The concept of opportunity is not fully understood in a rational way because in every opportunity there is a possible impossibility (or possibility of the impossible). Furthermore, possibility is not defined by knowledge of what can be.

In other words, the term threat is reffered to any phenomenon with the potential to harm interests of the state or society. This phenomenon can be natural (tindependent of human activity or can be caused by an entity endowed with will and intention, represented by an individual, group, organization or state).

Currently, it is customary to separate such types of threats at the state level [18]. These are military, terrorist, political, economic, social, environmental and threats caused by the action of natural forces.

Military threats include domestic and international conflicts that are resolved with the use of armed forces. This group also includes threats arising in the case of a military conflict in other countries, if the conflict consequences of the (political, economic, migration, and others) affect the interests of the defending community or the state.

Terrorist threats are threats to commit violent crime or to cause any harm in order to achieve declared goal or obtain a certain benefit in political, religious, criminal and other spheres.

Political threats – are threats of political pressure and promotion of other people's interests. They are the most often observed on the part of dictatorial regimes.

Economic threats are manifested in the growth of inflation, reduction of gross domestic product, closure of enterprises, reduction of the banking or stock exchange sector and others.

Social threats are mainly reduction of social guarantees, for example, provision of work, housing, medical care, inflow of immigrants, rise in prices for basic necessities and others.

Environmental threats are occurrence of industrial accidents and man-made disasters that lead to pollution of the natural environment: atmosphere, water basins and groundwater, the earth's surface, flora, fauna, etc.

Threats caused by the action of natural forces are called natural phenomena. These are floods and droughts, hurricanes and landslides, epidemics and pandemics, epizootics (wide spread of an infectious disease among animals) and epiphytotia (spread of infectious plant disease over the large areas).

Risk is a situation that has uncertain outcome with the mandatory presence of adverse consequences [19]. The situation is characterized as a one-act and unrepeatable occurrence of many events, coincidence of life circumstances and conditions that are revealed by human perception and activity. In other words, the situation is a deviation from the ideal picture. On the other hand it is a compulsion to make a decision. It is to have in mind a possible danger or to act at random in the hope of a happy outcome.

The word "risk" according to [20] is borrowed from the ancient Greek word meaning a rock or the foot of a mountain. Hence, the term "to risk" is translated from French and Italian as "to maneuver between rocks".

Some authors apply the term "risk" to real phenomenon (risk of a fire, risk of a car accident) and others authors apply it to a model of a real phenomenon built with the help of certain mathematical tools. It can be, for example, apparatus of probability theory and mathematical statistics, theory of fuzzy sets, interval mathematics.

Risk is an undesirable opportunity. Here, the term risk is used to describe an actual event. Risk is the probability of loss or failure to receive income compared to the predicted option [21]. In this case the term risk is used in the process of modeling of a real case using probability theory. Sometimes it creates confusion.

Therefore, the most comprehensive definition of risk [22] was initially used in the development of automated systems for forecasting and preventing events in aviation transport. Risk is a measure of quantitative multi-component measurement of danger, including amount of damage from exposure to security threats, probability of occurrence of these threats and uncertainty in the amount of damage and probability.

This definition of risk includes three components. Risk is (first of all) a measure of quantitative multi-component measure of danger, including amount of damage caused by the impact of security threats. Risk is (secondly) the probability of occurrence of these threats. And thirdly there are probabilities (or uncertainties) in the amount of damages. The authors of this article note that they choose their most acceptable risk description at each stage during the implementation of the project.

In addition, it should be noted that even after deciding on the interpretation of the terms threat and risk [23], practical implementation turns out to be quite difficult and time-consuming. It requires priority development of specialized mathematical apparatus used by large-scale (for example, a nuclear power plant) and individual (such as an experimental reactor) nuclear facilities.

4. Characteristic of the concept improvement areas of the optimal management of protected critical infrastructure object using the Pampuro method

The idea of the new concept implementation of optimal management of protected critical infrastructure object using the Pampuro method provides following five provisions.

The first provision is protected object selection.

This object can be any object of the state's critical infrastructure – from municipal gas distribution station which provides gas supply to domestic residential premises and enterprises (boiler plants, chemical plants, etc.) to the nuclear power plant which provides tens of percent of all electricity produced in Ukraine.

The second provision is determination of the security ensuring means of the object and the solved tasks.

Security of protected strategic object is assessed by the risk of any (the most incredible, hypothetical, sometimes bordering on fantasy) catastrophic event. General or total costs to ensure protected object security consist of two components. The first one is the preventing costs of catastrophic event. The second one is the liquidating cost of the consequences in the case of this catastrophic event. The given work shows that there is a certain (optimal) value of the risk of the occurrence of catastrophic event for each hypothetical catastrophic event. It corresponds to the minimum total costs. This minimum total costs is usually called limit of allocated funds to ensure security of protected object. It in turn provides a real (numerical) characteristic N_0 which takes into account all means involved in the object security.

In the general case the finite set consists of three subsets

$$N_0 = N_{01} + N_{02} + N_{03} \tag{1}$$

The first subset is danger detection tools. The second is means of prevention of danger. The third is means of consequences elimination in the case of danger.

Almost two years of the current war shows that the main danger to strategic protected objects located throughout Ukraine are air weapons – missiles and unmanned aerial vehicles (UAVs).

Based on this, the first subset of means of security ensuring of protected object includes means of detecting missiles and UAVs. It can be the widest range of stationary, mobile and portable radio equipment for detecting air targets. They can implement electromagnetic (radar), infrared (thermal), acoustic, optoelectronic, optical and other active and passive detection methods. This is not only technically sound electronic system, but also calculation that ensures its use for its intended purpose. This calculation should have several changes so that this technical system can function for a long enough time (hundreds of hours). This subset solves three main tasks:

- detection of danger (missiles and UAVs) approaching the protected object;
- recognition or identification of the detected danger;

- issuance of data for interception (destruction) of danger by the means of the second subset.

The second subset are means of preventing (destroying) danger. These can be various stationary, mobile and portable anti-aircraft missile systems (AAMS) designed to destroy various aerial targets. These can be: large-caliber and small-caliber anti-aircraft guns; stationary and mobile positions equipped with anti-aircraft small arms (large-caliber machine guns); means of radio-electronic warfare (REW) and camouflage. This subset solves one task: destroy or disable the means of air attack before they approach protected object. As in the case of the first subset, the components of the second subset are both technically servicable fire systems and their crew which ensure intended use. These crew should have several changes so that this technical system can work for a long time.

The third subset is means of consequences elimination in the case of danger. Even in the general case this subset consists of three groups. The first is fire and rescue crew with their technical means. These are fire, special engineering vehicles and special equipment designed for the disposal of unexploded ordnance and other explosive substances. These calculations should also be in constant readiness and with ability to eliminate consequences of catastrophic events for a long period of time. The second group is engineering technique used to dismantle rubble and extract (rescue) people from under rubble. As a rule these are mobile excavators, cranes, lifts and others. The third group is ambulances with medical teams. They are intended for providing first aid to victims on the spot and for evacuating wounded to medical facilities.

The third provision is the Pampuro method use.

Pampuro's method allows you to consider technological object from the point of security ensuring as an abstract hypothetical object. Its structure consists of elementary elements as an example of electronic circuit. This allows a single protected critical infrastructure object to be considered as a quadripole.

The input of the quadrupole receives information flow from all means of ensuring security of protected object N_0 which can be interpreted as accepted multi-frequency combinations of pulsed electromagnetic reflections from a radar target. Such sound combinations form meaningful phrase, full or partial spectrum that allows recognition of thermal or sound image. Of course, such reception of useful information flow cannot be without reception of informational interference (informational noise). The incoming mixture is considered additive. So, the flow of useful information is integrated with information noise and is further considered from spectral positions.

The fourth provision is definition of research goals of the abstract quadripole.

The following research goals of the abstract quadripole can be proposed taking into account material presented above.

The first goal of the study is to find frequency characteristic of abstract quadrupole. It will show how useful information is transformed with given parameters of the input information flow and information noise entering the input of the abstract quadripole.

The second goal of the study is to find optimal characteristic of the abstract quadrupole. It is determined by the Pampuro method as product of the optimal risk value (R_{op}) by the amount of the minimum cost (C_{min})

$$T_0 = R_{op} C_{\min} \tag{2}$$

This characteristic is primarily determined by the number of all means of ensuring security of protected object. Secondly, it should minimize the mean square of the error during the abstract quadripole functioning.

The fifth position is development of mathematical apparatus for solving problem of optimal management.

Mathematical apparatus is necessary to solve separate tasks to ensure safety of protected critical infrastructure object when the conditions for solving the problem are changed. For example, when security measures are increased or decreased, the operating conditions of technical means ensuring the main production process are changed.

5. Development of mathematical apparatus for different intensities of terrorist influence on nuclear facility

For example, let's consider a situation where the intensity of terrorist influence on nuclear facility grows exponentially over a limited period of time.

Let's introduce the following notation:

K_0 – coupling coefficient of an abstract quadrupole;

T_0 – characteristic of an abstract quadripole determined by the Pampuro method;

t_0 – initial countdown;

ω – circular frequency (ω_0 – initial circular frequency);

α– coefficient which shows the ratio of the information effect result on the abstract quadrupole to the square of the minimum transformation error of the entire information flow passing through the quadrupole;

σ_S^2– root mean square error;

H_0 – intensity of informational noise;

β – value determined by the information flow entering the system input;

Δ – shift in time determined by the operation time of the abstract quadrupole;

K(jω) – frequency characteristic of an abstract quadrupole that is physically realized;

A – intensity of influence;

t_ν – duration of exposure.

$$x\,(t) = s\,(t) + n\,(t) \tag{3}$$

where *n(t)* – informational noise in the form of stationary normal white noise with spectral density

$$S_n\,(w) = \frac{H_0}{2} \tag{4}$$

and *s(t)* – information flow from useful information, statistically independent of *n(t)*, which grows exponentially over a limited period of time (5) as shown in figure 2.

$$s\,(t) = \begin{cases} Ae^{\alpha(t-t_0)}, at \to t \le t_0 \\ 0, at \to t \succ t_0 \end{cases} \tag{5}$$

So, it is necessary to find complex frequency characteristic of abstract quadrupole which minimizes mean square error when the intensity of the input information flow increases according to the exponential law during a limited period of time. Its maximum will be determined by the intensity of exposure to A and its duration:

$$[s_v\,(t)]_{\max} = K_0 A^2 t_v \tag{6}$$

The square of the error in the operation of the abstract quadrupole will be equal to

$$E_{\min}^2 = \sigma_s^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_{s+n}\,(w)\,K_0\,(jw)\,dw = \frac{K_0 N_0}{2}\int_{-\infty}^{\infty}\frac{2}{w}\,(1-\cos wt_v)\,dw = \frac{K_0 N_0 A}{2} \tag{7}$$

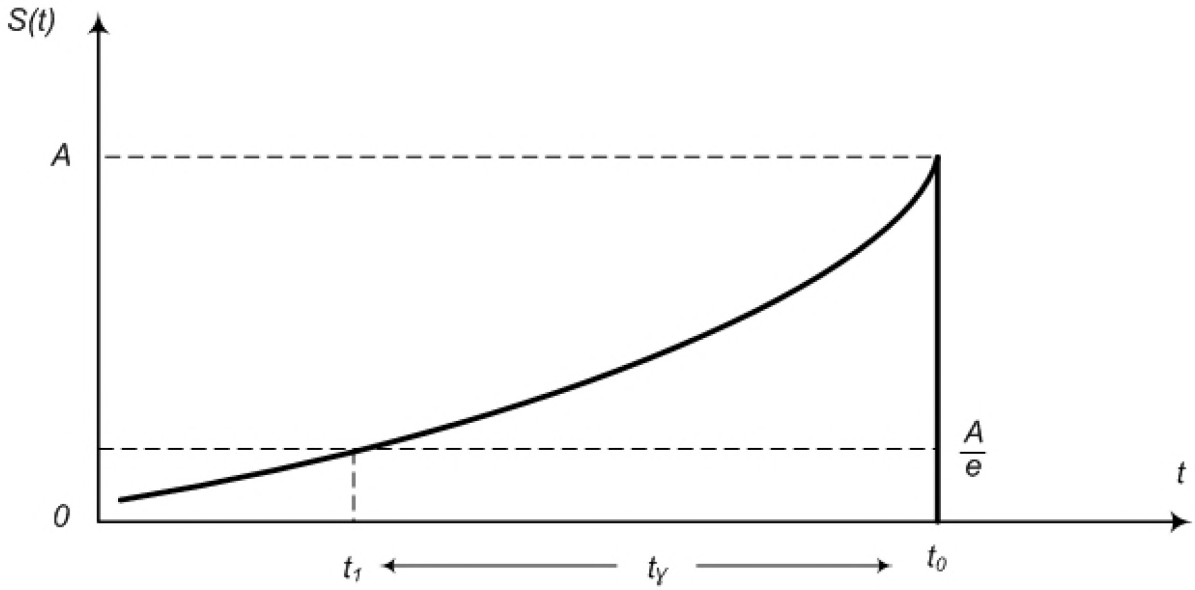

Figure 2. Scheme of flow growth according to the exponential law.

The relation (8) is defined according based on the fact that the optimal characteristic of the abstract quadripole, determined by the Pampuro method

$$T_0 = \frac{1}{\alpha} \tag{8}$$

coefficient α is defined as the result ratio of the information effect on the abstract quadrupole (7) to the square of minimum transformation error of the entire information flow passing through the quadrupole (8), i.e.

$$T_0 = \frac{N_0}{2At_v} \tag{9}$$

The frequency characteristic of abstract quadripole under the influence of an information flow grows according to the exponential law. In the conditions of white information noise it is described by

$$K_0\,(jw) = \frac{A}{jw}\exp\,(jwt_v) \tag{10}$$

Let's consider another case when the intensity of terrorist influence on a nuclear facility is maximum and persists for a limited period of time.

For the given case *s(t)* – information flow from useful information statistically independent *n(t)*, which in the moment t_1 for a limited period of time t_ν will have maximum to the moment t_2 (11), as it shown by figure 3.

$$s\,(t) = \begin{cases} A, at \to t_1 \le t \le t_2 \\ O, at \to t \prec t_1, t \succ t_2 \end{cases} \tag{11}$$

The final form of the frequency characteristic of abstract quadrupole under the maximum influence of information flow during a limited period in the conditions of white information noise is described:

$$K_0\,(jw) = A\exp\,(jwt_v) \tag{12}$$

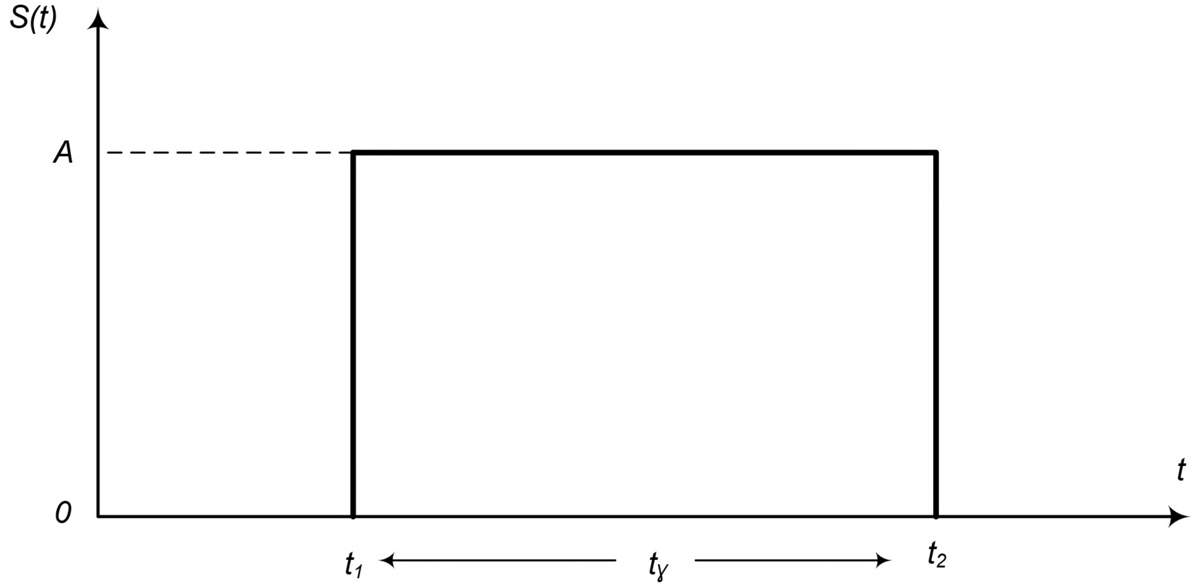

Figure 3. Scheme of maximum intensity maintaining of the incoming information flow during a limited period of time.

its maximum will be determined by the intensity of the impact A and its duration,

$$[s_v(t)]_{\max} = K_0 A^2 t_v \tag{13}$$

Square of the error in the abstract quadrupole operation will be equal to:

$$E^2_{\min} = \sigma^2_s = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_{s+n}(w)\, K_0(jw)\, dw = \frac{K_0 N_0 A}{2e} \tag{14}$$

Based on the fact that optimal characteristic of abstract quadrupole is determined by the Pampuro method (8):

$$T_0 = \frac{N_0}{2eAt_v} \tag{15}$$

So, we obtain frequency characteristic of abstract quadrupole under the influence of n information flow. Its maximum intensity is maintained for a limited period in the conditions of white information noise (12) and optimal characteristic of an abstract quadrupole is determined by the Pampuro method (15). Combination of these dependencies into system (16) will give the optimal characteristics of an abstract quadripole. It will be realized protected object with minimized mean square error at the maximum intensity of the incoming information flow. This is maintained for a limited period of time in the conditions of white information noise

$$\left.\begin{array}{c} K_0(jw) = A\exp(jwt_v) \\ T_0 = \frac{N_0}{2eAt_v} \end{array}\right\} \tag{16}$$

The developed mathematical software can be used as a unified software product by security services or physical protection services of various protected objects.

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6. Conclusions

Security methods developed based on the concept of deeply echeloned protection do not provide optimal security management of nuclear strategic objects – ensuring maximum security at minimum costs. Their practical implementation requires the development of a specialized mathematical apparatus despite the apparent simplicity of the eight principles of optimal management. It is applied to large-scale (for example, nuclear power plant) and to single (such as a research reactor) nuclear facilities.

One of the implementation areas of optimal security management is use of the Pampuro method. It provides following five provisions: selection of the protected object; determination of the ensuring security means and tasks solved by it; application of the Pampuro method; determination of research goals of the abstract quadrupole; development of mathematical apparatus to solve task of optimal management. The mathematical apparatus was developed using the Pampuro method to ensure security of the protected nuclear facility at minimum cost. It takes into account different intensities of terrorist influence. The software implementation of the developed mathematical apparatus can be used as a unified software product by security services or physical protection services of various protected objects.

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Features of designing systems for the formation of an internal microclimate of a high class of cleanliness of operating rooms of medical institutions

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Abstract. This publication is devoted to the study of the peculiarities of designing systems for forming an internal microclimate of a high cleanliness class in the operating rooms of medical institutions. The article presents an analysis of the requirements for microclimate hygiene and air environment of operating rooms of medical institutions, cleanliness classes of premises to be implemented with permissible air components and microclimate parameters for operating rooms of medical institutions, analysis of methods of microclimate regulation, analysis of the features of the construction of ventilation and air conditioning systems of high cleanliness class; analysis of air preparation systems for premises. The article identifies the features of ventilation and air conditioning systems and substantiates the need to use multi-stage filtration; installation of air conditioners with air recirculation and central air conditioning for fresh air preparation; creation of overpressure about neighbouring rooms; use of CAV and VAV systems to regulate airflow parameters and provide overpressure. Conceptual design solutions are presented, and typical block diagrams for the formation of an internal microclimate of a high class of cleanliness in operating rooms in a medical institution are developed, which can be used as standard ones in the development of design solutions. The necessity of developing an automation system is substantiated. A typical structural diagram of an automated air conditioning control system has been developed and substantiated. A generalising algorithm for subsystem functioning has been developed, which can be widely used in the design and construction of such systems.

1. Introduction

Modern treatment methods require specific microclimate conditions in wards, operating theatres, intensive care units, and the prevention of the spread of viruses and harmful bacteria between wards due to environmental pollution in healthcare facilities. Creating comfortable and appropriate environmental conditions in healthcare facilities is essential for successful surgeries and patient recovery.

Creating an internal microclimate of a high class of cleanliness is particularly relevant in operating rooms, where a mismatch in microclimate parameters can have several negative consequences, including unsuccessful surgery. Failure to meet the requirements of temperature conditions, especially during transplantation, can lead to infection and, subsequently, inflammation in the postoperative period and organ rejection. Clean rooms are mandatory for modern medical facilities, especially cell and tissue technology centres, to produce medicines, medical devices, etc.

The development of modern science and technology and changes in regulatory and legal support require finding new solutions for constructing premises, especially high-cleanliness operating theatres in healthcare facilities.

When constructing indoor climate systems, special attention is paid to using energy-efficient technologies to minimise the company's costs and environmental impact. Given Russia's full-scale invasion of Ukraine, it is essential to conserve energy resources and find new and effective energy-saving technologies. Therefore, research on improving the systems and equipment for creating an internal microclimate of high cleanliness in operating premises is relevant.

The **aim** of the work is to design systems for the formation of an internal microclimate of high cleanliness in the operating rooms of medical institutions.

2. Theoretical background

2.1. Analysis of the requirements for microclimate hygiene and air environment in the operating rooms of medical institutions

In modern medicine, the cleanliness of the premises plays an essential role in the adequate performance of operations and the recovery of patients [1–3]. Therefore, in the construction of medical facilities, great attention is paid to the,materials used to decorate walls, floors, ceilings, furniture and plumbing fixtures (heating appliances, plumbing fixtures, etc.). Ventilation and air conditioning systems (VAC) ensure clean premises [3, 4].

According to research by the World Health Organization (WHO), purulent inflammatory diseases have increased significantly over the past ten years abroad and in Ukraine. An analysis of HAIs has shown that their duration and frequency depend on the state of the ambient air environment in healthcare facilities. Medical personnel are the primary source of the "release" of various bacterial particles and microorganisms while moving around the room. The intensity of the appearance of new particles and microorganisms in the airspace is influenced by temperature, the degree of mobility of people, and the speed of air movement. They move with air currents, which creates the possibility of them getting into a patient's open wound on the operating table. It is impossible to influence the movement of healthcare workers, so maintaining the desired temperature, air flow rate, and air exchange is a priority to minimise the likelihood of "infection". Therefore, operating theatres have special requirements for creating suitable microclimate parameters.

Multi-stage air purification and unidirectional air distributors ensure the required microclimate parameters in operating theatres. The need to ensure the boundary's shape and the straightness of air movement over the area selected for protection, in which the surgical table is located, has been identified [3, 5]. The airflow in the room should maintain the microclimate parameters [6,7] and assimilate harmful factors (heat, odour, humidity, toxic substances), protect the selected areas from possible infections and ensure the air purity required in the operating room.

The approaches and concepts of building such systems are covered in [8, 9].

2.2. Analysis of ways to regulate the microclimate of a high purity class

Filtration methods based on airflow displacement are widely used to prevent the ingress of bacterial contamination into critical areas. For this purpose, laminar air distributors of various designs have been developed [3], which are built into the ceiling structure above the area of the room requiring aseptic conditions.

The flow of displacement air moves slowly in small sections from top to bottom so that the sterile areas of the operating theatre and the areas where sterile materials are handled are separated from the environment. The air is removed simultaneously from the lower and upper areas of the room to be protected [3].

Designers usually use unidirectional ultra-fine airflow air distributors in operating theatres with built-in ceiling filters. A large volume of airflow slowly moves down the room, separating the area to be protected from the ambient air. However, many experts need to pay more attention to the fact that such solutions are insufficient to maintain the required level of air purification during surgery.

The high air exchange rate keeps the supply airflow close to isothermal. Due to the large surface area, laminar flow systems with high air exchange rates provide a low initial flow rate. Controlling changes in room air pressure and the operation of the exhaust system minimise air recirculation zones. To ensure an acceptable level of bacteriological cleanliness of the air environment, the operating frequency of air exchange is approximately 25 times per hour, and in some cases, even less. The air is removed through exhaust vents symmetrically placed on the walls of the lower zones. Smaller laminar flow units distribute smaller amounts of air. They are installed directly above critical areas of the room in islands in the centre of the room rather than occupying a large part of the ceiling area.

The observations made it possible to establish that laminar air distributors sometimes provide unidirectional flow due to the difference between the temperature in the air jet and the temperature of the ambient air environment. The vertical low-temperature laminar flow velocity will increase as you descend towards the floor. The flow acceleration increases as the supply air volume increases and the temperature decreases relative to the room air. The "unidirectionality" is not maintained at higher flow rates. As the air moves from the starting point, the flow lines run parallel and then the flow boundary changes and narrows towards the floor, thus not protecting the area defined by the size of the laminar flow unit. The airflow at a speed of 0.46 m/s draws inert air from the room. In addition, bacteria are constantly entering the room, which means that contaminated particles will be introduced into the airflow coming out of the air intake. The air recirculation facilitates this due to the air pressure in the room.

To maintain cleanliness in the operating room, it is necessary to ensure air imbalance by increasing the air supply by 10% more than the exhaust. Excess air gets into neighbouring unclean rooms. In modern operating theatres, sealed sliding doors are often used, so excess air circulates the room without going outside and then is drawn back into the supply system with the help of a built-in fan, where it is filtered, cleaned and reintroduced to the room. The circulating air flow collects all the pollutants from the room air. If the flow boundaries are breached, air from the interior space will inevitably enter the flow, and harmful particles will enter the sterile area that needs to be protected.

Increased air mobility leads to the detachment of dead skin particles from the exposed skin of the healthcare professional, which subsequently enters the incision. On the other hand, infections during the postoperative rehabilitation period result from hypothermia, which is exacerbated by the moving flow of cold air. Therefore, conventional laminar air distributors that work well in clean production environments can be beneficial and detrimental during surgery in conventional operating theatres.

Proper air circulation and distribution in a room requires the selection of an air inlet panel of sufficient size, as well as a standard flow rate and temperature of the supplied air. However,

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more is needed to solve the issue of air disinfection [4, 5, 10–13]. Properly designed ventilation and air conditioning systems (VAC) prevent the accumulation and spread of infectious diseases, which can minimise the spread of viruses, fungal spores, bacteria and other biological pollutants through the air. When designing a VAC for operating rooms, it should be taken into account that the design of the air supply system should be aimed at minimising the entry of HAIs into clean areas through the air and ensuring the highest possible level of cleanliness in the rest of the operating room. In addition, it is necessary to conduct epidemiological monitoring of the air in the operating room. However, the complexity of such measurements during operations and the need for an approved methodology for collecting and counting microorganisms to assess the level of air purity would require more than such monitoring.

Particular attention should be paid to the location of supply and exhaust devices to ensure the required air conditions in the operating theatres. When designing, it should be noted that using the entire ceiling and floor area is impossible, and the location of exhaust devices on the floor needs to be more hygienic needs to be more hygienic (challenging to clean, quickly contaminated). The analysis of customer requirements and completed projects has shown that the most common are the "island" placement of laminate panels above the protection zone, especially in small operating rooms and the placement of exhaust holes in the lower part of the room's walls.

To prevent contaminated ambient air from entering the laminar flow, air curtains are used, which are constantly working on the exhaust, creating a protective barrier in the form of a narrow "shell" of air with a higher velocity, which is created around the perimeter of the ceiling. To prevent the effect of narrowing the laminar flow and stabilise the required velocity, the exhaust slots of air curtains should be placed along the perimeter of the laminar flow. This will stretch the airflow, expanding and filling the entire area under the air curtain. Design errors or improper installation of the air curtain will have negative consequences – the functioning of the air curtain as a laminar system, without providing the required functionality; high air suction rate at which the airflow does not reach the operating table, which can lead to the threat of leakage of LBW into the operating area from the floor level; curtains with insufficient suction rate may not completely block the airflow and be sucked into it. The need to install an air curtain is determined by the purpose of the operating room and the cleanliness class.

2.3. Analysis of the features of the construction of a high purity class's ventilation and air conditioning systems

The research and analysis of regulatory and legal support made it possible to identify the specifics of the VAC:

- presidential air conditioners are used to ensure and maintain precise temperature and humidity parameters;
- only supply air conditioners are allowed in clean and medical premises;
- split systems are allowed in administrative premises of healthcare facilities and laboratories;
- materials and structural elements of air ducts and filtration chambers must be adapted for regular washing and disinfection;
- it is necessary to install a multi-stage filtration system (at least two filters of different degrees of purification) and use HEPA (High-Efficiency Particular Airfilters) as final filters;
- ensure the required level of air exchange by creating an overpressure relative to neighbouring rooms.

To summarise the above, let us define the main tasks set for cleanroom air handling systems: supplying the required volume of supply air and distributing it throughout the room; preparing the supply air according to the specified parameters (humidity, temperature, purification); organising the required direction of air movement throughout the room.

If there are several cleanrooms, each of them uses a different class of filter or requires a different supply air velocity, the resistance of the branches with these filters will change unequally. This means that the airflow rate during the cleanroom operation will gradually differ from the required one, even with initially balanced network branches. Special measures must be taken to compensate for this effect, one of which is frequency regulation. However, frequency-controlled power supplies in variable-impedance networks are only effective for one room, as they can only support the total air flow rate. CAV (Const Air Volume) flow controllers convert a VAV (Variable AIR Volume) system to a CAV system to address this situation. The basic idea is to keep the resistance of the CAV system constant when operating together with the HEPA filter. That is, as the HEPA filter's resistance increases, the CAV controller's resistance should decrease proportionally. This algorithm ensures that a constant airflow is maintained in rooms with a high class of cleanliness and guarantees automatic stabilisation of several clean rooms during operation, even in the absence of frequency control.

In order to meet the acoustic requirements when using the H14 filter, not only must a duct sound attenuator be used, but the CAV controller must also be factory-coated with a sound attenuating coating. The air ducts before and after the CAV regulator must also have a noise-absorbing coating. It is worth noting that using duct sound attenuators requires increased pressure developed by the air handling unit. A distinctive design feature of CAV controllers is the impossibility of its complete closure, i.e. the CAV controller cannot act as a shut-off valve. For "dirty" rooms, the ability to cut off the branch when changing the filter is a prerequisite. The CAV controller must be retrofitted for these rooms with a shut-off valve. In order to reduce the installation space required for the CAV valve and the shut-off valve, a VAV controller with a constant flow function can be used. Depending on the application, the VAV controller can act as a CAV controller with the ability to maintain constant or multiple air flow rates and act as a shut-off valve. If the VAV is equipped with a differential pressure sensor, it can maintain an overpressure in rooms with a high cleanliness class or create a negative pressure in dirty rooms.

The cost of an air circulation system is proportional to the airflow rate. A creative approach to the design of a cleanroom requires keeping airflow to a minimum. This can be done, for example, by:

- Careful consideration of the air purity requirements, including analysing risk criteria to avoid imposing excessively high air purity requirements;
- using turbulent flows wherever possible;
- providing a high degree of protection only for those stages of the process where the risk analysis requires it;
- Reducing the area with unidirectional airflow to an absolute minimum, taking into account the risk factor;
- minimising the speed of unidirectional airflow, taking into account the process geometry, the instability caused by it and the upward heat flows from heat sources;
- Limiting critical areas with unidirectional airflow by using partitions or plastic curtains.

To achieve a compromise between quality and flexibility of solutions on the one hand and capital and operating costs on the other, open cooperation between the designer, supplier and cleanroom user is essential.

2.4. Analysis of air treatment systems for high-cleanliness premises

Among such systems, we should note systems with indoor air recirculation, integrated air conditioning systems for clean rooms with non-directional (turbulent) flow, and integrated air conditioning systems for high-cleanliness rooms with unidirectional flow. Let us make a brief analysis of these systems.

Room air recirculation systems protect a small area, such as a research laboratory. Such work areas are autonomous installations connected to the network and use the room's air. The HVAC system controls the temperature and relative humidity in the room. Due to the difficulties with temperature and humidity control and maintaining an appropriate noise level, dense installation of such devices in one room is undesirable.

Integrated air conditioning systems for cleanrooms with non-directional (turbulent) flow combine air circulation and outside air in a typical circuit. When using turbulent airflow, the final stage with HEPA filters is added to the air supply system and fed directly into the air distributors, where the HEPA filter and diffuser are combined in one housing.

To minimise the risk of cross-contamination, the same air conditioner is only used in rooms with the same purpose. If several individual air conditioners are used, a unique air conditioner must be provided for the outdoor air preparation of the central air conditioner. Each supply air conditioner serves a separate zone of the building, consisting of rooms that can use the same air.

To prevent pollution of the natural environment caused by the presence of highly active or toxic pollutants from the process, a separate exhaust is provided to the atmosphere after proper air purification through air filtration. Air circulation is the most efficient approach in terms of energy saving. However, in cases where the risk of cross-contamination is high, air circulation is not possible even with HEPA filters, and all ventilation and air conditioning systems must be operated with outside air.

In order to reduce heating and cooling costs, a water/glycol heat exchanger is used to exchange energy between the outside air and the exhaust air. In winter, the outside air is heated by the energy in the exhaust air. In summer, the outside air is cooled by the exhaust air.

Integrated air conditioning systems for high-cleanliness rooms with unidirectional flow are used to achieve maximum protection with minimum effort. Such systems allow for a wide range of combinations to meet design needs. There are three main principles of protection: local, linear and zone.

The following algorithm is proposed for the preparatory stage of designing ICS for operating rooms of medical institutions:

(i) To analyse the requirements for microclimate hygiene and air environment of medical institutions' operating rooms to determine the cleanliness classes of the premises to be implemented with permissible air components and microclimate parameters.

(ii) To analyse how to regulate the microclimate of a high cleanliness class to determine the acceptable way of implementing design solutions.

(iii) Analyse the features of the construction of ventilation and air conditioning systems of a high purity class to determine the need for multi-stage filtration; installation of air conditioners with air recirculation and a central air conditioner for fresh air preparation; creation of overpressure about neighbouring rooms; use of CAV and VAV systems to regulate airflow parameters and provide overpressure.

(iv) Analyse the air preparation systems for high-cleanliness rooms to determine the feasibility of using recirculating air ventilation and air conditioning systems, an integrated air conditioning system for clean rooms with turbulent flow, or an integrated air conditioning system for high-clean rooms with unidirectional flow.

3. Results

3.1. Design

It is necessary to analyse the premises for the implementation of design solutions, analysis of design tasks, architectural and construction drawings of the project, applicable regulations and state standards. Based on the analysis of the source above documents for the design and considering the location of the facility, it is necessary to determine the characteristics of the construction area.

The next step is to analyse the location of the premises, investigate the building's features, get to know the functional purpose of the premises, and determine the cleanliness classes. For example, let us consider premises on two floors requiring appropriate solutions to create an internal microclimate of a high cleanliness class for operating rooms in a medical facility. We classify clean rooms and areas. When determining the cleanliness class, we consider the location of the premises and the technological features of air ducts in the building. The defined cleanliness classes for all rooms of the design object are the initial data for calculating the supply air flow rate and making conceptual decisions on forming an internal microclimate of a high cleanliness class of operating rooms and further system design.

We carry out the necessary calculations of the supply air flow rate. The air supply in a room of a given cleanliness class is determined by a calculation method that considers the requirements for excess heat and humidity, carbon dioxide emissions and permissible concentrations of colony-forming units (CFU). The calculation of the air exchange rate in terms of harmfulness is carried out according to the methodology given in the designer's manual. The external supply air is pretreated before being supplied to the high-cleanliness class premises to comply with the set temperature and humidity parameters and to remove contamination. Pre-treatment is costly, so the design should minimise the outside air used for energy efficiency. The results of the calculations are presented in the form of tables. Having calculated the total amount of supply air and the amount of air to be removed from the intensive care unit, we obtain the following data: supply air – 10030 m3/h; exhaust air – 10330 m3/h. The air that needs to be more for the exhaust systems of the bathrooms is supplied from the hall and corridors that are not part of the clean area. The calculations are used to develop conceptual design solutions.

3.2. Development of conceptual design solutions

Based on the calculations performed, it is proposed to use a ventilation and air conditioning system with air recirculation and outdoor air preparation in the central air conditioner to provide the operating premises with a microclimate, which is proposed to be improved with a recuperator with an intermediate heat carrier (glycol) to recover the heat of the exhaust air, a constant air flow valve on the supply to each room, and a variable flow valve on the exhaust branch from each room to maintain the pressure drop between the rooms. For rooms not used 24/7, we use constant air flow valves with an electric drive to select a mode of 100% capacity or 50% and the ability to turn off the air supply, i.e. 100/50/0% operation.

The use of separate supply and exhaust systems is recommended. Separate mechanically driven supply and exhaust systems should be provided to ensure standardised temperature, humidity, and air purity parameters that meet sanitary, hygienic, comfort, and technological requirements, with air exchange for clean rooms. Air handling units for clean rooms should be implemented in a hygienic design with backup fans.

As a rule, ventilation equipment is located in specially designated rooms (ventilation chambers) on the roof. The air exchange in the room should be calculated based on the assimilation of hazards and taking into account the requirement to prevent the movement of air from more polluted areas to less polluted ones. This ensures sanitary and hygienic conditions for different cleanliness classes of premises. Air distribution and exhaust will be carried out using diffusers and ventilation grilles located in the plane of the suspended ceiling and connected to the supply and exhaust units by air ducts. If the premises of the operating and intensive care units are located on two floors, it is recommended to divide them into separate groups of rooms, each of which will be served by separate supply and exhaust ventilation systems. The temperature in the premises is assumed to be 22°C, and the humidity – 55-60%. The relevant parameters are maintained automatically. Maintaining humidity at 55-60% also protects against electrostatic effects.

The temperature and humidity in the room will be monitored by sensors that will be installed in the recirculation air duct as close as possible to the room to be served. Appropriate sensors will monitor the temperature and humidity of the supplied air, and a maximum humidity hygrostat is proposed to be installed in the supply air duct within the room, close to the laminate panel.

According to the technological task, indoor air cleanliness class is ISO7 in operating rooms and ISO8 for intensive care, anaesthesia, preoperative and other clean rooms. For outdoor air and for systems serving clean rooms, we offer 4-stage air purification in filters. The air will be supplied to the upper zone and removed from the two zones of the room with a distribution of 40% from the upper zone and 60% from the lower zone.

In operating theatres, automatic maintenance of the set pressure drop is recommended. For this, a constant airflow regulator should be installed on the supply line and a variable airflow regulator on the exhaust line. The variable airflow regulator will be triggered by a signal from a pressure sensor installed in the room.

The ventilation of the premises should be organised in such a way as to prevent the flow of air masses from "dirty" zones (rooms) to "clean" ones. Airflow regulators should maintain the required pressure drop with high-speed drives, which are recommended to be installed on exhaust air ducts. They should be controlled by a signal from differential pressure sensors, which should be installed in the room to be served. Supply air treatment units should include steam humidifiers to maintain the relative humidity in their rooms. Steam humidifiers should be installed on the technical floor to be "fed" with water from the building water supply system. The steam from them will be fed through a steam distributor into the air duct.

Ventilation systems for operating theatres and intensive care units should have 100% redundancy to ensure uninterrupted operation. Outside air intake for ventilation systems should be organised in a clean area. Exhaust air should be discharged at a height above the roof. Air handling units should be equipped with water and electric heaters to heat the air in the winter. With this approach, during the warm period, the standard air parameters will be ensured by cooling the air in water heat exchangers. Refrigeration machines, which are recommended to be installed on the roof, should be used as a source of cold.

The selection of air distributors in all premises is proposed to be based on the estimated air flow rate on the premises and take into account the regulatory requirements for speed and temperature difference in the working area of the premises. Air ducts laid outside the building should be insulated with mineral wool products with a thickness of at least 50 mm and covered with a casing. Air supply ducts inside the building are proposed to be insulated with foamed rubber insulation. It is proposed to install shut-off and control valves on all branches of air ducts to air distribution and air intake devices.

The following measures are proposed for more efficient use of energy resources: automation of air conditioners will allow programming a reduction in the temperature in the premises at night or after hours; use of equipment of a high energy efficiency class; installation of check and air valves; use of external enclosing structures with thermal performance that meets the latest regulatory requirements; installation of recuperators with an intermediate heat carrier to utilise heat from the exhaust.

The next design stage is the development of block diagrams for indoor climate control systems. We make design decisions, taking into account the architectural layout of the premises on the floors and the possibility of laying air ducts. For example, we decided to divide the ventilation and air conditioning systems into two systems to reduce the cross-sectional area of the air ducts and, accordingly, the height to which the false ceiling will drop.

The next design stage is the development of block diagrams for indoor climate control systems. Considering the architectural layout of the premises on the floors and the possibility of laying air ducts, we make design decisions. For example, the decision to divide the ventilation and air conditioning systems into two systems to reduce the cross-sectional area of the air ducts and, accordingly, the height to which the false ceiling will drop.

To prepare the air supplied to the operating rooms serving the operating rooms and provide the rooms that are part of the clean area but not related to the operating rooms, with supply and exhaust air, a ventilation and air conditioning system with a central air conditioner is proposed. To ensure the multiplicity of air exchange and a given microclimate, it is proposed to use a separate air conditioner with recirculation and fresh air mixing to ensure sanitary standards for each operating room. Excess air should be pushed out into rooms not part of the clean area. The following design stage is the final equipment selection and laying of air ducts on architectural plans.

Structural control model for distributed ventilation systems. As a result of the study of medical centre operating rooms and construction approaches, it is recommended to develop an automated control system for air conditioning systems that provide a microclimate directly in operating rooms and supply and exhaust systems that prepare air for these systems and provide ventilation to other cleanroom areas to ensure proper air quality and quantity. The ventilation system for intensive care units is recommended to provide heating and cooling of the air, while other systems should provide for heating only. A centralised control system should be used.

The analysis of approaches to automation, the subject area of research, and the requirements for cleanroom ventilation allowed us to form a block diagram of the automated air conditioning control system, which is shown in figure 1. It can be widely used at design facilities with minimal adaptation. An automated system of three modules, M1-M3, should be built. Module M1 is an input unit responsible for reading data from the measuring equipment necessary for decision-making. Module 2 is an information processing and decision-making unit. This unit is the central unit that processes the information from the measuring equipment and makes the appropriate decision on the necessary actions in the system. The M3 module is an output unit that controls mechanical devices (actuators). The number of control subsystems and actuator units can be adapted to a specific medical facility, but the construction concept will remain the same.

This example shows that the M1 module includes six sensor units responsible for monitoring the corresponding subsystem. Let us consider the example of an air conditioning automation system for one operating room, which is typical:

- room air temperature sensor, Troom (T5);
- supply air temperature sensor, Tsa (T3);
- fan pressure difference sensor, Pfp (PDI);
- differential pressure sensor on the filter, Pf (PDI);
- air flow sensor, DPS;
- overheating thermostat of the electric heater, Th;
- control panel for the PKM subsystem.

Assuming that subsystems 1-3 have the same structure, the sensor units and actuators of these subsystems will be the same, figure 2 and figure 3.

The analysis of implemented systems and our own experience suggest that the M2 module usually includes a programmable logic controller (PLC), which is used to automate the control of actuators of such systems. The PLC processes information from the devices of the M1 module

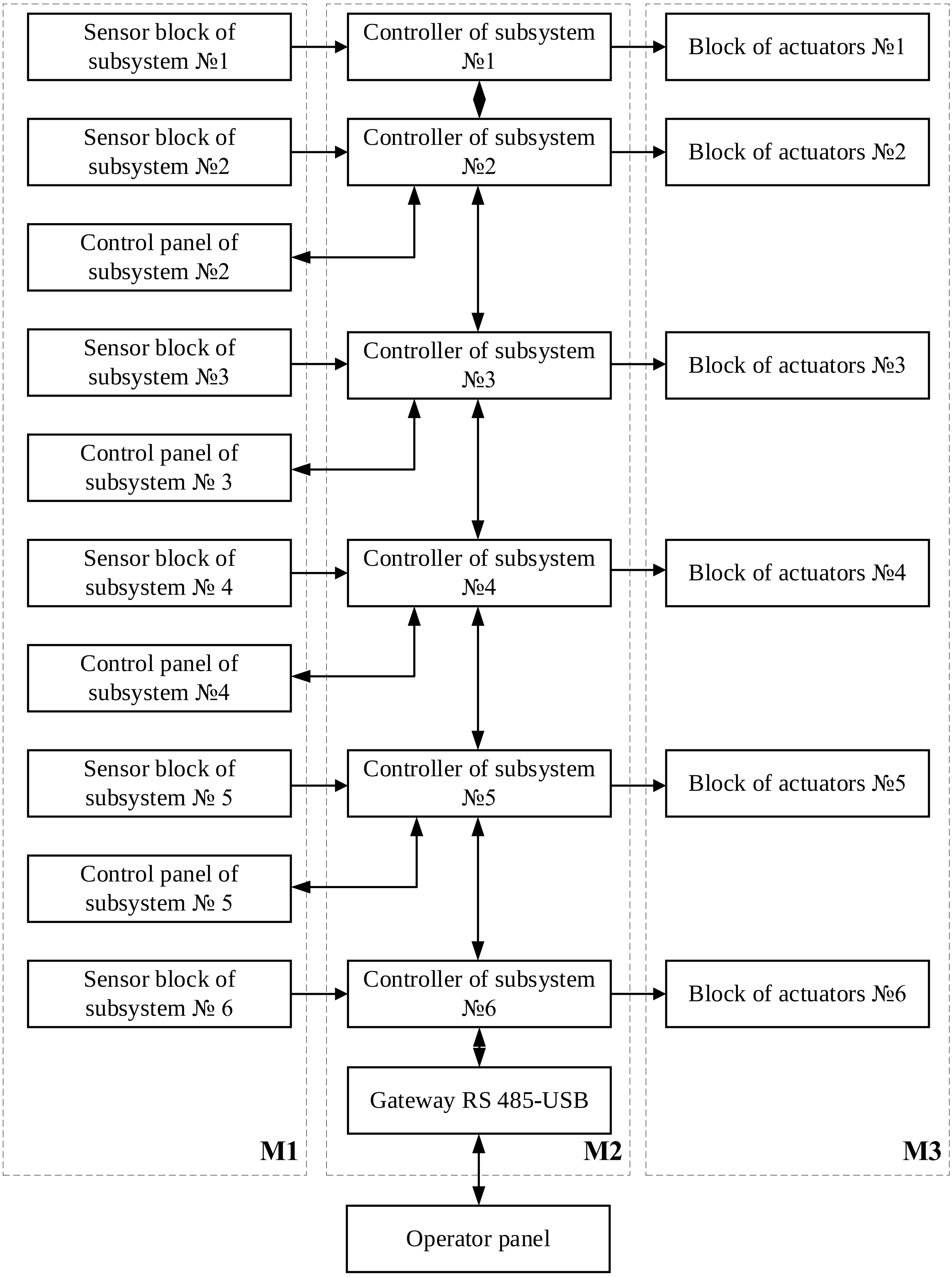

Figure 1. Block diagram of the automated air conditioning control system.

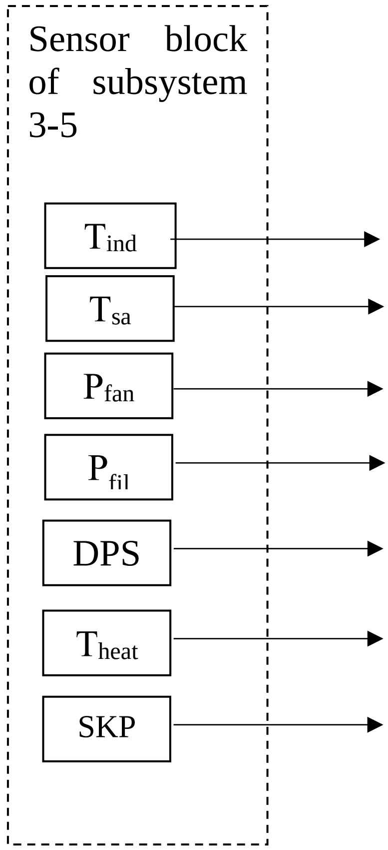

Figure 2. Block diagram of the sensor unit of subsystem 3.

and, based on the processing of the received information, makes decisions on the control of the actuators of the M3 module.

A typical actuator unit includes: relay units, RB1 – RB3; variable airflow device, VAFD; supply air fan, Fsa; electric heater, K; coolant pump H; three-way valve of the water cooler; alarm indication device, Ia; frequency converter of the supply fan, FC.

In modern conditions of building automated control systems, it is proposed that remote control of the developed system be used. A typical model of interaction between system components is shown in figure 4. The model provides for the organisation of data transmission via twisted-pair cable using the RS-485 interface and the Modbus-RTU protocol.

The central control panel allows you to continuously receive and archive all data on the operation of the automatic control system of air conditioning units, in particular:

- View the current parameters of the engineering system and make adjustments to its operation (switch on/off equipment, change the values of control parameters, set time schedules for equipment operation, etc.;
- analyse data from the archive and event logs and, based on the analysis, make adjustments to the operation of the equipment.

Using the Internet and a mobile device (tablet, laptop, smartphone) or a desktop PC that must have an Internet browser with HTML5 support, you can use the WEB server to remotely control or switch systems on/off. No additional software installation is required. The central control panel (CCP) must have a static IP address on the Internet. The data from the measuring

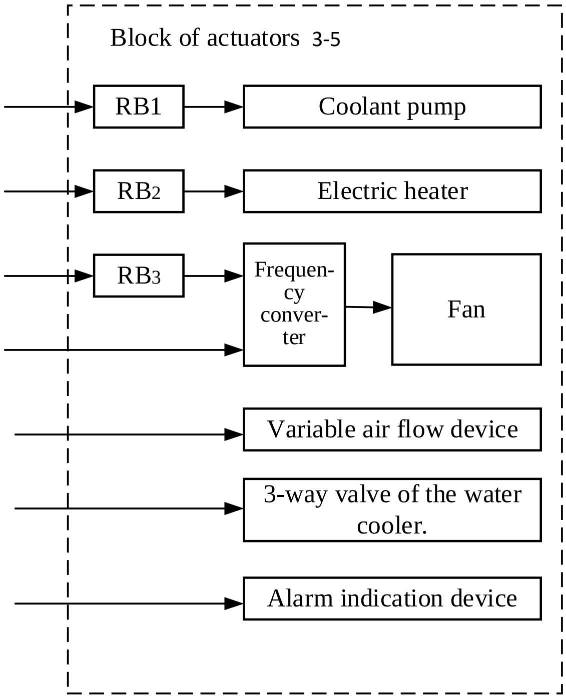

Figure 3. Block diagram of the actuator unit of subsystem 3.

equipment is read from the controller and displayed on the control panel screen in the software interface in real time. If necessary, it is possible to make changes to the operation of air conditioning units in real-time.

Analysing the purpose and tasks of each structural module of the system allows for determining the requirements for the subsystem functions and selecting equipment. The developed system is an integrated system. It can operate in both automatic and manual modes. In the automatic mode, the system reads sensor data, processes it and controls actuators to maintain the set indoor climate parameters. On the other hand, its operation requires human intervention to clear an alarm, adjust operation, set parameters, and switch it on and off. The power supply of module 2 consists of step-down transformers from 220 V to 24 V for each subsystem.

3.3. Development of a functional air conditioning control scheme for the operating unit

A functional diagram is developed based on the structural diagram of the system's functional modules and a thorough analysis of the requirements for the system and the installation site. The functional diagram shows the connection of actuators and measuring equipment to the controller of the respective system, indicating the type of inputs/outputs. In addition, this diagram should show the assignment of measuring equipment and actuators to subsystems. Typical control objects are a servo drive of a variable airflow device, a servo drive of a three-way valve of a water cooler, a coolant pump motor, an electric motor of a supply fan that supplies air to the room, and electric heaters that heat the air if necessary. In addition, the subsystems can provide for smooth control of the supply fan motor speed using a frequency converter (FC) to maintain a constant airflow rate on the HEPA filters. In the next stage, selecting the element base to draw up the electrical schematic diagram of the system and ensure the specified functionality is necessary.

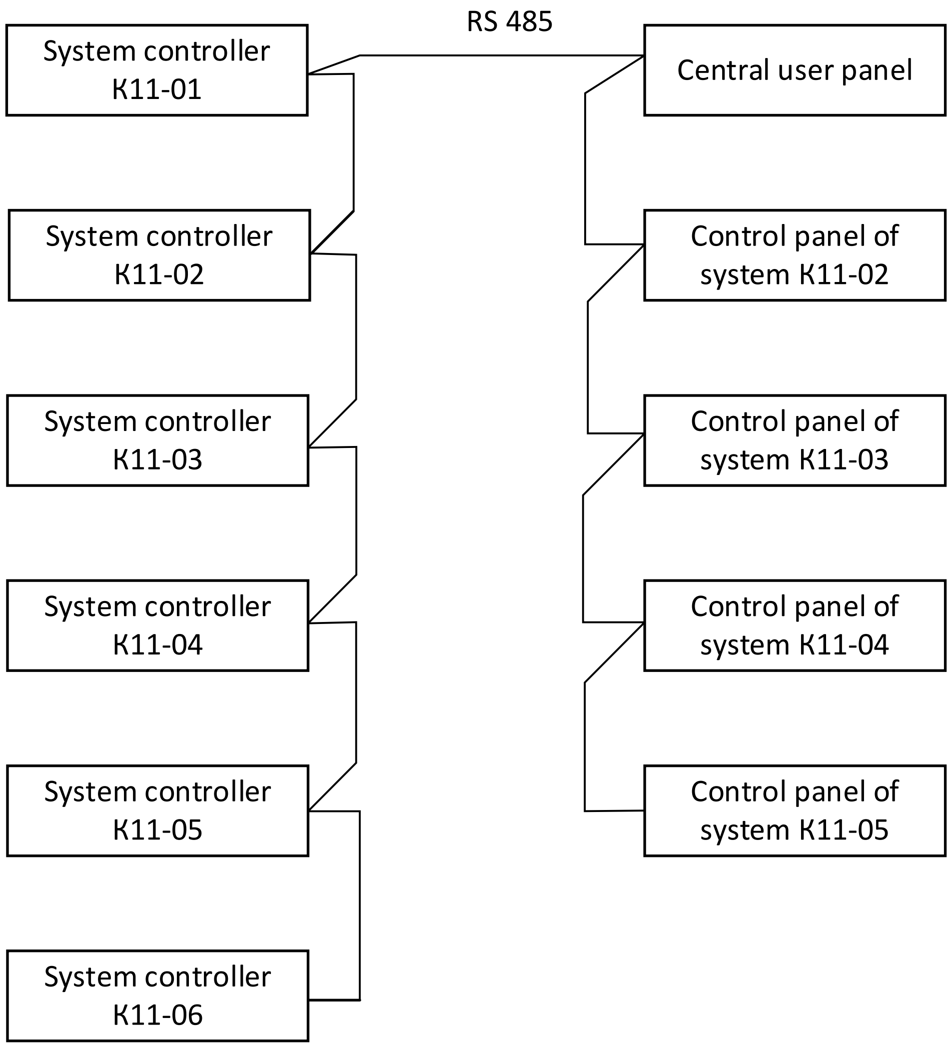

Figure 4. Interaction model of a centralised remote control system.

3.4. Block diagram of the subsystem operation algorithm

The generalised algorithm of the subsystem operation is shown in figure 5. This algorithm shows the system's generalised operation that provides the operating room's microclimate. As can be seen from figure 5, operations related to the removal of the emergency (blocks 17, 18), switching on (block 5) and switching off the system (block 23) are performed by a person, except in cases provided for by the emergency shutdown of the system.

The system starts to operate when it is switched on by a person (operator) through the operator panel or on the control panel using the power button. The system is at rest until it receives a signal to switch on the system (block 5). Next, the fans are switched on (block 7), and the fan switch-on is checked (block 8) using data from the PDI pressure difference sensor. The next step is to read the data from the airflow sensor (block 9). Next, the data received from the supply air flow sensor DPS is checked against the system setpoints (block 10).

Depending on the results obtained, the system proceeds to read the temperature sensors (block 11) if the air flow rate is equal to the setpoint. Otherwise, it checks whether the air flow rate exceeds the setpoint (block 1). If the airflow rate is higher than the set value, the frequency converter reduces the frequency of the supply fan (block 2). If the airflow rate does not meet

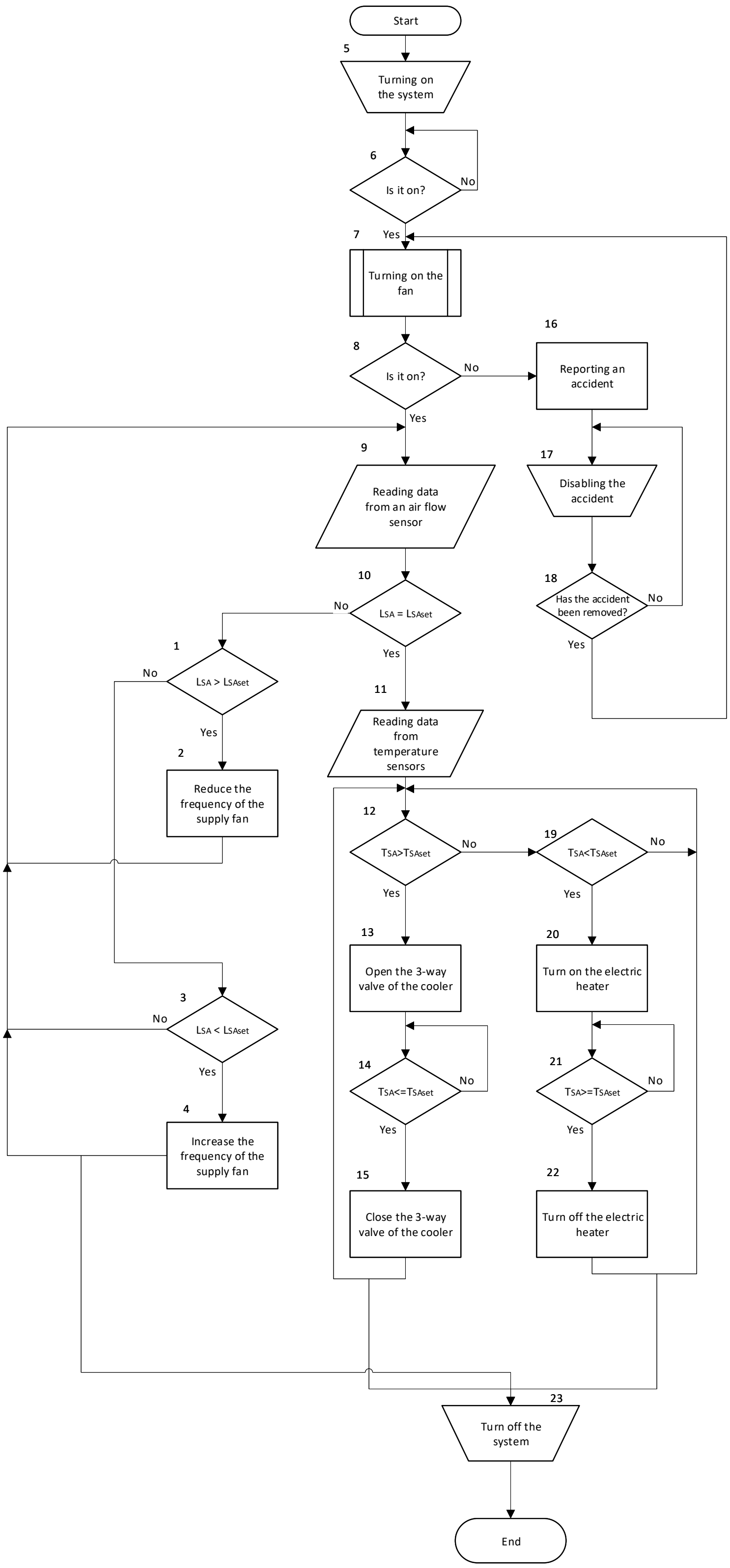

Figure 5. Generalised algorithm of subsystem 4 (K1) functioning.

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the condition, check whether the air flow rate is not less than the set value (block 3). The fan speed increases if the flow rate is lower (block 4). Then, the flow rate is rechecked to ensure it equals the set value (block 9). Moving on to reading the data from the temperature sensors (block 11), we check Tpp>Tppz (block 12).

If the temperature is higher, the three-way coolant supply valve to the air cooler is opened, and then the condition Tpp≤Tppback is checked (block 14); if Tpp meets the condition, the three-way cooler drip trap is closed (block 15), and then we return to checking the condition Tpp>Tppback (block 12).

If the Tpp>Tppz (block 12) is not valid, the condition Tpp<Tppz (block 19) is checked for compliance. If the condition is met, the electric heater is switched on (block 20). Next, the condition Tpp≥Tppz (block 21) is checked. If the condition is proper, the electric heater is switched off (block 22), and we return to checking the condition Tpp>Tppz (block 12). If not, we wait until the condition is fulfilled.

Optionally, at any stage, the system can be switched off (block 23).

4. Conclusions

As a result of the analysis of the requirements for microclimate hygiene and air environment of the operating rooms of medical institutions, the cleanliness classes of the premises for implementation with permissible air components and microclimate parameters for the operating rooms of a medical institution were determined. The analysis of methods for regulating the microclimate of a high cleanliness class made it possible to determine an acceptable way to implement design solutions, namely using airflow displacement due to laminar and turbulent air flows.

The analysis of the features of the construction of ventilation and air conditioning systems of a high class of purity made it possible to highlight the features of ventilation and air conditioning systems, which made it possible to determine the need to use multi-stage filtration, installation of air conditioners with air recirculation and a central air conditioner for fresh air preparation; creation of overpressure about neighbouring rooms; use of CAV and VAV systems to regulate airflow parameters and provide overpressure. It is established that the design and materials of air ducts, filter chambers and their elements should be adapted for regular cleaning and disinfection. The analysis of air treatment systems for high-cleanliness premises has made it possible to establish that it is advisable to use ventilation and air conditioning systems with air recirculation for operating rooms.

As a result of the research, approaches to the design of systems for the formation of an internal microclimate of a high class of cleanliness of operating rooms of medical institutions, which are typical and can be used as a reference, have been proposed. Several recommendations have been developed to improve methods and approaches to constructing such systems.

A typical flowchart for forming an internal microclimate of a high class of cleanliness of operating rooms in medical institutions has been developed. The peculiarity of these solutions is the introduction of a central air conditioner to ensure the system's functioning. To ensure the multiplicity of air exchange and a given microclimate in each operating room, it is proposed to use a separate air handling unit with recirculation and fresh air mixing to ensure sanitary standards. Separate exhaust systems are recommended to remove air from the bathrooms and showers of the male and female sanitary checkpoints. Excess air should be pushed out into rooms not part of the clean area.

As a result of the study of one of the operating units of the medical centre, which is located on the second floor and the ventilation system scheme for this room, it was decided that in order to ensure the proper quality and quantity of air, it is necessary to develop an automation system for four air conditioning systems that provide a microclimate directly in the operating rooms, and two supply and exhaust systems that prepare air for these systems and provide ventilation for other rooms of the clean area. The analysis of automation approaches, the subject area of the study, and the requirements for cleanroom ventilation allowed us to form a block diagram of an automated air conditioning control system, which includes an input module responsible for reading data from measuring equipment necessary for decision-making; an information processing and decision-making module; and an output unit designed to control actuators. As a result of the conducted research and based on the developed structural diagram of functional modules, the functional diagram of the system was developed, and the system element base was selected. A generalising algorithm for the functioning of subsystems has been developed.

The results of this study can be used as methodological materials in the design and construction of systems for the formation of an internal microclimate of a high class of cleanliness of operating rooms of medical institutions. It contains generalised recommendations for the design of such systems, the main algorithmic and functional actions.

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Abstract. Currently, there is significant focus on the transition to green energy, particularly in achieving climate neutrality. The European Green Deal outlines one of the main approaches in this field, which is being implemented in the EU. As Ukraine aims to become an EU member, it would be beneficial to consider adopting renewable energy solutions, especially in heating and cooling systems, in order to align with the EU's efforts towards sustainability. The statistical analysis of the field shows that Ukraine's share of renewable energy is two and a half times less than that of the EU, but it still exceeds that of three EU member states. It is worth noting that the majority of renewable energy for heating in Ukraine is generated by biomass, which is considered less economical and ecological compared to heat pumps. At present, there is a notable interest in increasing the proportion of renewable energy used for heating and cooling, with heat pumps being the primary focus. Various methods are being investigated to facilitate the adoption of heat pumps, including government assistance to reduce system costs and step-to-step realisation in cases of limited financial resources.

1. Introduction

At present, there is considerable attention being given to the topic of a green transition, especially with regards to the move towards renewable energy sources as a substitute for conventional fossil fuels. However, there is a number of different understandings on how to value and define the topic of green energy transition [1].

One of the approaches being considered is the European Green Deal [2]. This set of policy initiatives was first presented in 2019 by the European Commission with the aim of achieving climate neutrality for the European Union (EU) by 2050 [3]. Any new member of the EU is expected to be in line with this [4], so it is crucial for Ukraine to adopt the same policy.

Defining climate neutrality is a crucial aspect of this topic. The term 'climate neutrality' generally refers to achieving net zero emissions of all greenhouse gases or solely carbon dioxide, depending on the context. This necessitates balancing emissions in and removal from the atmosphere during a specific period of time [5]. According to the International Energy Agency's (IEA) annual report for 2023 [6], further progress is required to achieve the goal of net zero emissions by 2050, as outlined in its 2050 Net Zero Emission Scenario. The report identifies a lack of state regulation and clear goals as major obstacles to achieving this target. The scenario aims to limit the temperature increase to 1.5 °C above pre-industrial levels, as outlined in the Paris Climate Agreement [7].

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When it comes to the direction of green energy transition in energy supply, there are three main directions:

(i) electricity;
(ii) heating and cooling demands;
(iii) transport.

Traditionally, it has been observed that a significant amount of attention has been directed towards the transition to green energy in the field of electricity production. For instance, the article [8] that analyzed the demand for personnel in renewable energy development was primarily focused on renewable electricity production. However, it is noteworthy that heating and cooling account for almost 50% of the EU's total gross final energy consumption [9]. Therefore, it may be beneficial to conduct additional analysis to determine the current trend in the EU and Ukraine for renewable share in heating and cooling as well as to explore potential strategies for increasing the proportion of renewable energy sources in Ukraine.

2. Comparison of the share of renewable energy in heating and cooling in EU and Ukraine

To examine the share of renewable energy in Ukraine and the EU, it is crucial to carefully review statistical data. However, it can be difficult to obtain such data due to the current Russian war against Ukraine. That war began with the Russian aggression and occupation of Ukrainian territories since 2014 and escalated with Russia's full-scale invasion against Ukraine in 2022, has made it challenging to access up-to-date information on the energy sector as it is not shown due to the martial status. Therefore, the analysis is based on the latest data provided in the source [10], which pertains to the conditions of 2020.

Figure 1 shows the share of renewable energy used in heating and cooling systems in Ukraine, the EU, and its members. Based on this data, it can be observed that:

(i) Ukraine's share (9.28%) was almost two and half times lower than the EU's share (22.98%).
(ii) Ukraine had a higher share than three EU member countries: Belgium (8.45%), the Netherlands (8.05%), and Ireland (6.26%);
(iii) the three largest economies in the EU have a share of either less than (Germany at 14.48% and Italy at 19.95%) or only slightly higher (France at 23.27%) than the EU.

3. Analysis of the share of renewable energy in heating and cooling in Ukraine

The following analysis presents the types of renewable energy sources used for heating and cooling in Ukraine from 2014 to 2020. The data is displayed in table 1. Based on this data, it can be observed that:

(i) the majority of renewable energy used for heating and cooling is generated by biomass, with other energy sources accounting for no more than 2.5% as shown in figure 2;
(ii) biomass energy is primarily derived from solid biomass, while biogas makes up less than 1%;
(iii) biomass is mainly consumed by private households. However, there has been a decrease in the share of private households from almost three-quarters to two-thirds of that consumption during the selected period from 2014 to 2022, as shown in figure 3;
(iv) heat pumps are the only other type of renewable energy with a share of more than 1% of the total share of renewable energy. The share of air heat pumps among all types of heat pumps is always much higher than 50%, as shown in figure 4. It should be noted that the potential for heat pump implementation is considered a way above the current level of its current implementation, especially in the district heating system [12];

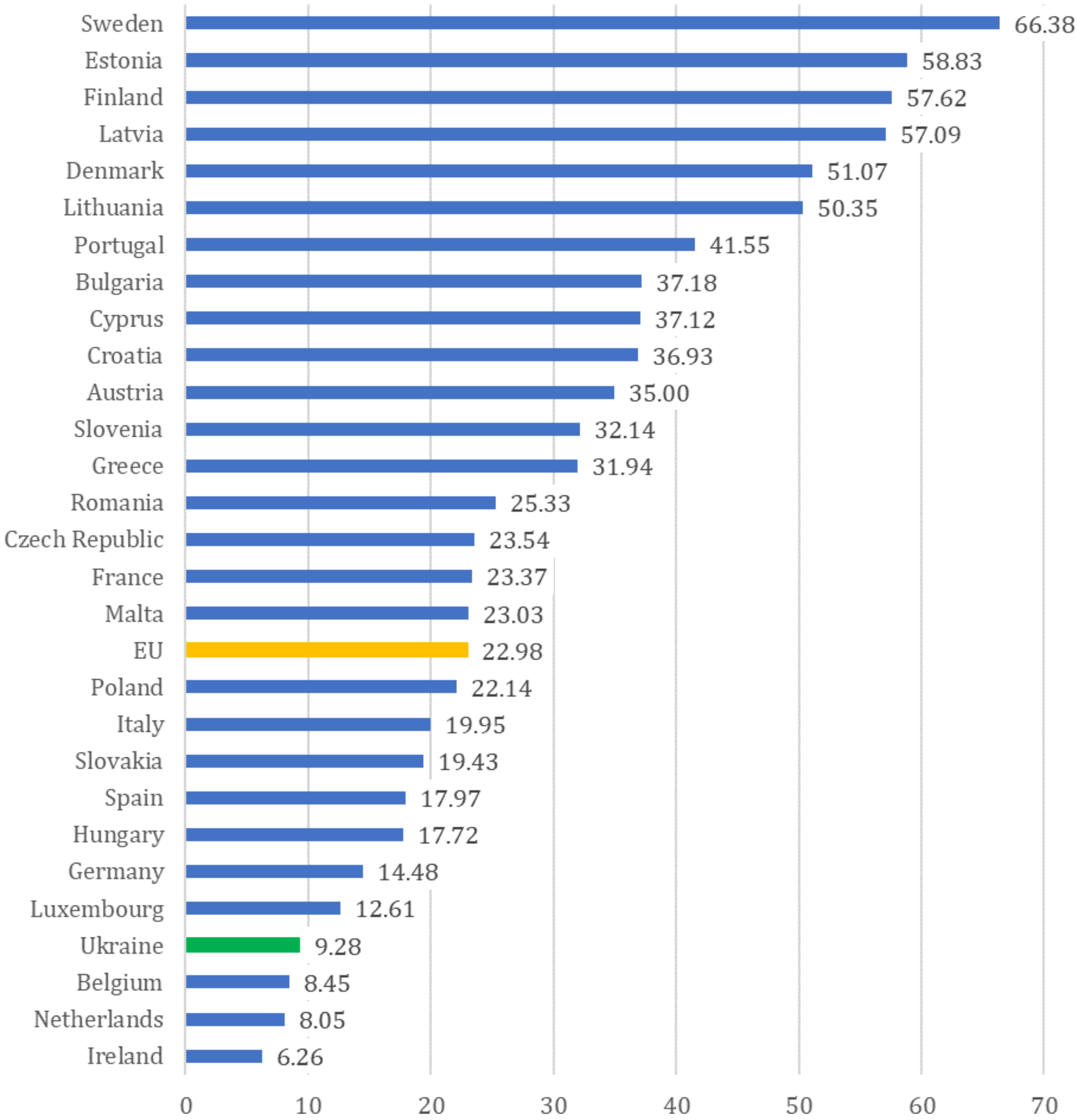

Figure 1. The share of renewable energy used for heating and cooling in Ukraine and the EU and its members, %.
Note that the data for Ukraine is taken from [10], while the data for the EU is taken from [11].

(v) the share of other renewable energy sources is either negligible, as in the case of solar energy, or not reported at all, as in the case of geothermal energy (except for heat pumps).

(vi) data suggests that district heating and cooling systems are not currently utilizing renewable energy.

Table 1. Amount of energy produced from different types of energy sources for heating and cooling in Ukraine, ktoe, based on data from [10]

Type of renewable energy	Amount of energy generated, ktoe						
	2014	2015	2016	2017	2018	2019	2020
Geothermal energy (except for heat pumps)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar energy	0.1	0.1	0.5	0.5	0.6	0.6	0.6
Biomass:	1408.3	1533.8	2170.5	2432.1	2673.6	2783.3	2816.1
solid	1408.1	1525.2	2154.2	2412.4	2652.1	2762.6	2796.7
biogas	0.2	8.6	16.3	19.7	21.5	20.7	19.4
bioliquid	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heat pumps:	0.6	0.6	21.4	25.4	64.7	68	51.7
air-source (aerothermal)	n.a.	n.a.	15.7	18.1	37.2	37.9	36.2
ground-source (geothermal)	n.a	n.a.	3.6	4.6	17.2	18.8	9.7
water-source (hydrothermal)	n.a.	n.a.	2.1	2.8	10.4	11.3	5.8
TOTAL	1409.0	1534.5	2192.4	2458.0	2739.0	2851.9	2868.4
From TOTAL:							
district heating and cooling	0.0	0.0	0.0	0.0	0.0	0.0	0.0
biomass for private households	1069.2	1096.1	1505.7	1677.4	1812.2	1857.1	1891.6

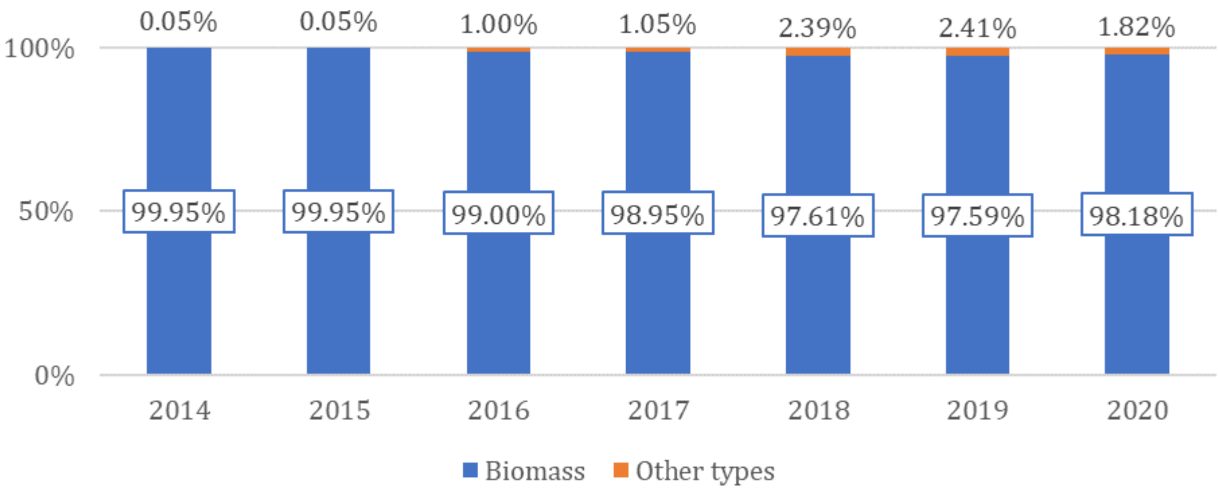

Figure 2. The share of biomass in heating and cooling for Ukraine in relation to the total share of renewable energy in heating and cooling, %, based on data from [10].

4. The future of biomass and heat pumps in Ukraine

In relation to biomass, it is worth noting that there are differing opinions on which types of biomass should be classified as a renewable energy resource [13] or a green energy source due to their environmental impact [14]. For example, a comparison between a biomass boiler and a heat pump revealed that the biomass boiler system emitted air pollutants, including greenhouse gases, at a significantly higher rate than the heat pump [15].

When considering the economic aspects of biomass boilers and heat pumps, it is important to

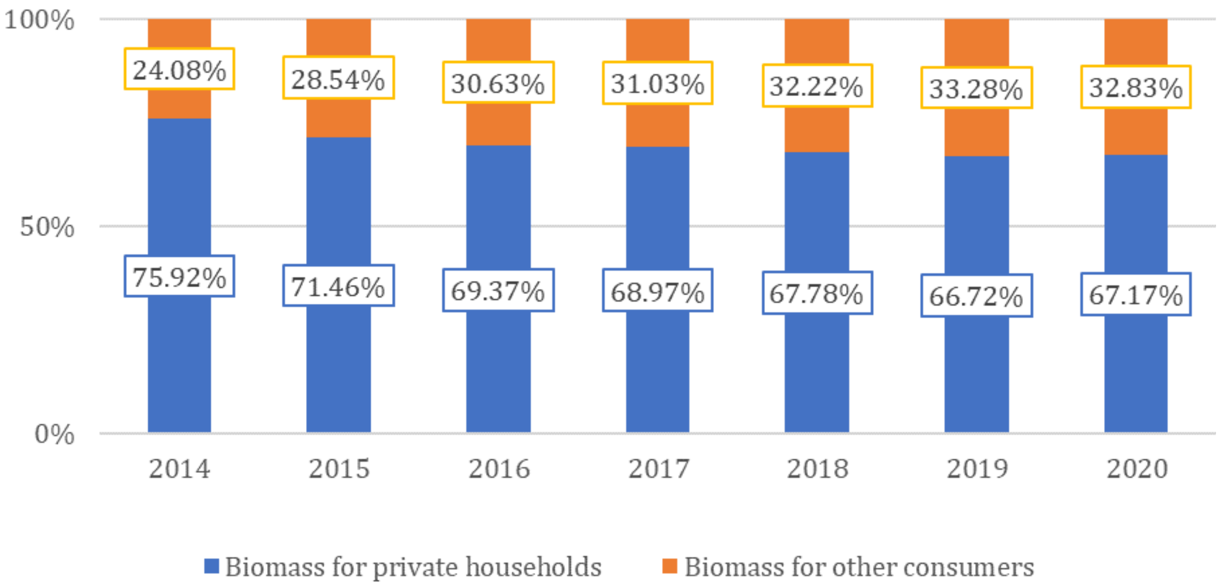

Figure 3. The share of biomass in the heating and cooling of private households in Ukraine in relation to the total share of biomass in the heating and cooling, %, based on data from [10].

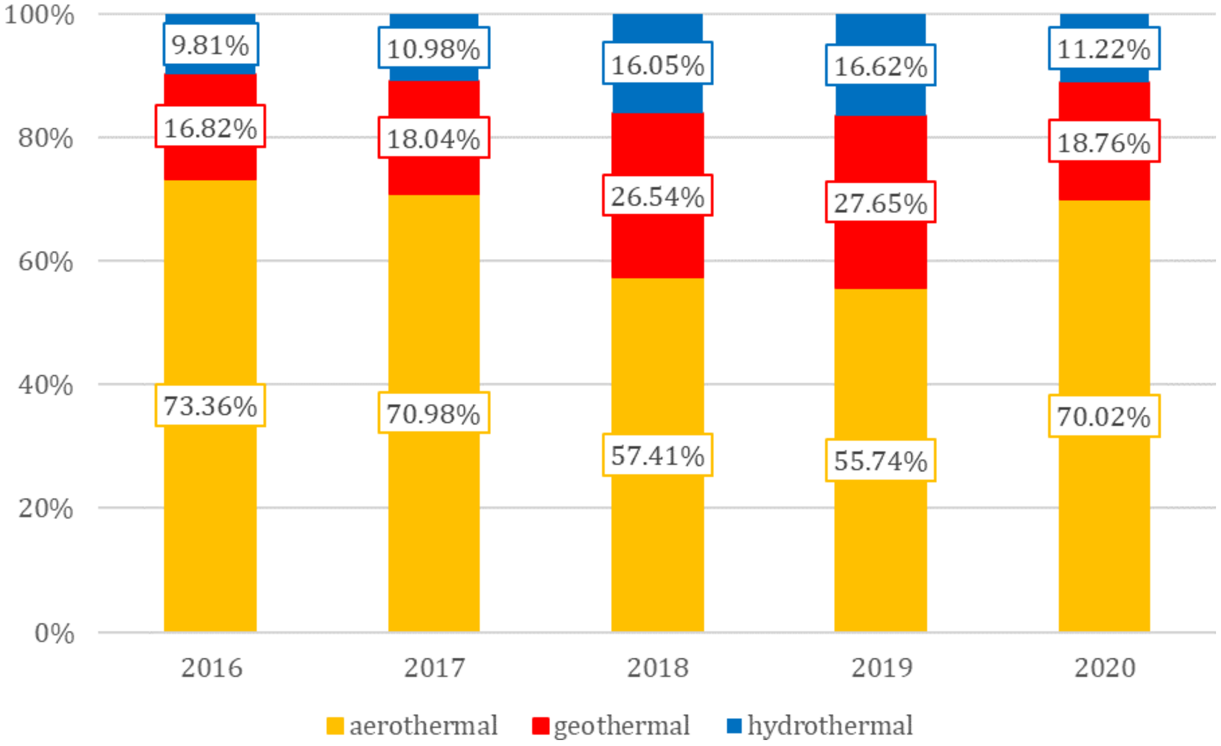

Figure 4. The share of different types of heat pumps, %, [10].

take into account the method of comparison. When comparing the energy efficiency of different heating systems, the concept of levelized cost of energy (LCOE) is commonly used. In this particular case, it is also referred to as levelized cost of heat (LCOH) since the cost of heat is being analyzed. The LCOH value is determined using the following formula [16, 17]:

$$LCOH = \frac{\sum_{t=1}^{n} \frac{(C_t + M_t + F_t + T_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Q_t}{(1+r)^t}}, \ \$/\mathrm{MWh_t}\ , \tag{1}$$

where C_t is the capital expenditure of the system in the year t, \$; M_t is the operation and maintenance expenses in the year t, \$; F_t is the fuel cost in the year t, \$; T_t is the carbon tax cost in the year t, \$; $(1 + r)^t$ is the discount factor in the year t with the discount rate r (%) for that year t; Q_t is the heat generated in the year t, $\mathrm{MWh_t}$; n is a heating system lifetime, year. It is worth noting that the price of conventional fossil fuel F_t, \$, in the European region has increased significantly due to the full-scale Russian invasion against Ukraine. As a result, measures have been introduced to conserve these resources, making renewable energy sources a more cost-effective option [18].

When calculating LCOH, it is important to take into account the specific context of the system, including its temporal, spatial, and scale-related aspects. As noted in [19], the LCOH of the natural gas boiler was comparatively lower (30%) than that of ground-source heat pumps for individual heating, based on data from the United Kingdom in 2018. In 2021, just three years later, data from IEA revealed that the levelized cost of energy (LCOE) for ground-source heat pumps in the UK had become equivalent to that of gas boilers [20]. Furthermore, based on the data [20], it appears that the LCOH of pellet boilers is notably higher than that of heat pumps.

As previously mentioned, it is important to take into account the scale of the system. This involves considering not only the potential decrease in LCOH with increased capacity, but also the possibility of utilizing other cost-reducing technologies. For example, exploring the potential of seasonal thermal energy storage systems [21] and optimizing the use of wind or solar energy to power heat pumps [22]. Therefore, district heating with heat pumps may be a more financially competitive option, especially in densely populated areas.

In summary, it can be observed that there are both economic and financial reasons for the increase in the use of heat pumps for heating and cooling. As of 2021, heat pumps have covered approximately 10% of global space heating needs, and this figure is on the rise due to various state programs aimed at promoting their use [23].

In Ukraine, the level of heat pump usage is relatively low due to limited financial resources. To address this issue, a step-to-step realisation to implementing district heating pump projects was proposed in [24]. This realisation considers not only the implementation of the heat pumps themselves, but also the thermal insulation and the retrofitting of a heating system inside the buildings. The choice of which part of the system to modernise first is based on the sequential selection of parts of the system based on the shortest of their payback periods in the case of modernisation. A similar approach was proposed in [25].

5. The prediction of future heat pump share in renewable heating in Ukraine

It is of great importance to assess the future share of heat pumps in overall heating and cooling consumption in order to facilitate the transition to renewable energy. This evaluation helps to track progress and determine the pace and timing of reaching milestones in this area. The aforementioned pace can be influenced by a number of factors, including legislation and the availability of funding [26].

There has been a degree of criticism regarding the predicted share of heat pumps in Ukraine being significantly higher than what may actually occur. This criticism was highlighted in the market study [27] which provided a rather conservative evaluation of the possible future share of heat pumps (and the number of heat pumps) in household building in Ukraine. For the year 2040, there were two scenarios: the higher share level was that 8% of households could be provided by heat pumps, while the lower one was approximately 4%. The primary rationale for this assumption was the annual average growth rate of the EU's heat pump market, which was estimated to be approximately 10% between 2009 and 2018.

It is worth noting that the growth rate of the heat pump market was significantly affected by the full-scale Russian invasion against Ukraine. According to a report by the European Heat Pump Association [28], annual sales of heat pumps in 15 European countries increased by 37.6% in 2022 compared to 2021, but then decreased by 5% in 2023 compared to 2022. This decrease can be attributed to several factors, such as the stabilisation of energy prices in Europe, consumers delaying purchases in 2023 to take advantage of expected higher subsidies in 2024, or the removal of government subsidies in some countries.

An alternative approach to forecasting this share was presented in [26], which also drew on information from [29]. In contrast to the previous source [27], this information focused on providing data on the amount of heat generated by heat pumps. As indicated in [29], by 2040 in Ukraine, the annual amount of heat Q_{el+b}^{2040} generated by electrical heat pumps and electrical boilers is expected to reach 192.2 million Gcal, while the general annual heat generation $Q_{heating}$ is expected to reach 359 million Gcal. Furthermore, in [26] it is stated that the proportion of heat pumps in heating η_{el}, in combined heat generation by heat pumps and electrical boilers, is expected to be 0.92. Consequently, the ratio of heat provided by heat pumps in 2040 is anticipated to be:

$$\eta_{el} \times \frac{Q_{el+b}^{2040}}{Q_{heating}^{2040}} \times 100\% = 0.92 \times \frac{192.2}{359} \times 100\% = 49\%. \tag{2}$$

This value is considerably higher than that predicted in the previous forecast: 49% vs. 8%. Despite the differing areas addressed (all consumers and residential only) and characteristics employed (amount of energy produced and total number of heat pumps installed), this fluctuation highlights the pressing necessity for a more comprehensive evaluation of the optimal methodology for forecasting the growth of the heat pump market in Ukraine.

Some of the ideas presented in [30] can be utilised as a basis for future research in this field. In particular, while the analysis of future heat pump share was done in [26] using the average value of the coefficient of performance of heat pumps, it was proposed in [30] to create several scenarios with different proportion of air-source and ground-source heat pumps. It should be noted that the classification of heat pumps in [30] is different from the classification of heat pumps shown here.

Conclusion

In conclusion, the results of this analysis show that:

(i) the data from 2020 indicates that Ukraine's share of renewable energy in heating and cooling is 9.28%, in comparison to the EU's share of 22.98%. Ukraine's share is higher than that of three EU countries (Belgium, the Netherlands, and Ireland) but lower than that of the largest EU economies (Germany, Italy, and France), whose shares are either less or only slightly higher than the EU's share.

(ii) the data from 2020 indicates that biomass is currently used almost exclusively (over 97.5%) as a renewable energy source for heating in Ukraine. Over 99% of this consumption is solid biomass. Private households account for the majority of this consumption, but that share declined from almost three-quarters to two-thirds during the period from 2014 to 2022.

(iii) although the proportion of heat pumps in renewable heating and cooling is currently relatively small, it is anticipated that this will increase. However, in order for the models used to forecast the growth of the share of heat pumps in renewable heating and cooling systems to be accurate, they must align with the actual market conditions. Currently, the methods used to calculate the growth forecast of the heat pump share are quite disparate, and the expected share of heat pumps in providing renewable heating and cooling can differ by several times. This necessitates the undertaking of further work to enhance the proposed methodologies, which would be founded upon the actual market and forecast not only the share of heat pumps in general, but also individual types.

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Gypsum recycling using an inclined chamber vibrating jaw crusher

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Gypsum recycling using an inclined chamber vibrating jaw crusher

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Abstract. The construction of new buildings and the demolition of obsolete and war-damaged buildings generate hundreds of thousands of tonnes of drywall waste. Gypsum waste, harmless in an isolated state, when thrown into a landfill causes environmental problems by polluting groundwater, emitting hydrogen sulphide and greenhouse gases. The solution of such an urgent problem, coinciding with the purpose of this work, is possible through the development of effective technological schemes and equipment for processing waste into secondary raw materials. The research on the selection of the lining plate of the jaws of the vibratory jaw crusher has been carried out on the impact bench. The dependence of effective destruction of gypsum layer of drywall on the profile of lining plates is shown. Drywall was crushed in a laboratory crusher. The innovative technological process allowed to separate the initial composite material into three constituent parts converted into secondary raw materials. The obtained results substantiate the feasibility of processing drywall waste in a vibratory jaw crusher at the place of its formation and obtaining at the same time marketable products, reducing transport costs, improving the environment and preserving mineral resources.

1. Introduction

Gypsum, according to Protodyakonov scale, belongs to rather soft materials and is widely used in construction, agriculture, art models, pharmaceutical, chemical, food and other industries. The density of gypsum is 2.3 – 2.8 g/cm^3, hardness on the Mohs scale is 2, and the texture is massive. Gypsum mining is carried out by underground or open-pit methods. In this case gypsum quarries occupy huge areas of the earth surface suitable for agricultural and industrial production. The general view of known gypsum quarries is shown in figure 1.

USMining forecasts that global demand for gypsum will grow at a rate of 2.5% over the next few years. It is estimated that by 2030 the global demand for gypsum will reach 300 million tonnes. The largest volume of gypsum is mined in the USA, Iran, and Canada. In Ukraine, the first place in the number of reserves and production of gypsum and anhydride is occupied by the Donetsk basin, where a significant part of the explored deposits are located in the Bakhmut district. A large number of enterprises are located in the Lugansk region and Crimea [1, 2]. All these enterprises are located in the temporarily occupied territory and in the war zone, so the main production of gypsum is carried out in the Carpathian region. The decrease in production can be partially covered by processing industrial and construction waste gypsum

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(*a*)

(*b*)

Figure 1. Gypsum quarries: a – Almeria; b – Nyrkivske.

materials. In construction, gypsum powder is used in building finishes, gypsum blocks, as a binding component in concrete to improve its properties.

However, the predominant use of gypsum is for the production of drywall [1]. The boards are two sheets of specially made paper (cardboard) between which a dense gypsum filler is placed. The finished gypsum board includes 92...93 % of gypsum 6...7 % of cardboard and 1 % of additives. The standard length of plasterboard is taken as 2, 2.5 or 3 metres, the width of sheets is mainly 1.2 metres, thickness varies from 6.5 to 24 mm. [3]. The global drywall market is growing at a high rate. This is fuelled by the growth in residential construction, renovation and modernisation of old buildings. A huge amount of drywall will be required in the reconstruction of war-ravaged cities in Ukraine. The global drywall market is expected to grow from 15.08 billion square metres in 2023 to 20.37 billion square metres by 2028 at a compound annual growth rate of 6.19% during the forecast period (2023-2028) [4].

The increase in the production of drywall predetermines an increase in construction waste, which can be generated from several sources [5]. In the construction of new residential buildings, supermarkets, shopping and office centres, warehouses, industrial workshops, etc., waste (trimmings) is generated in the process of cutting drywall sheets to the required dimensions (figure 2, a) and discarding sheets or their individual parts that have mechanical damage. This group of waste is relatively easy to sort, clean and store. As a result of crushing, gypsum is obtained, the purity of which is sufficient for its use in the production of new drywall panels. Similar conditions occur in the production of new gypsum drywall. For example, from the drywall produced at the Powered plant in 2019, approximately 5,700 tonnes (internal and external scrap) were sent to landfill [6].

When demolishing and renovating obsolete buildings and structures, drywall waste can be sorted and stored in the process of dismantling the panels. This rational technology greatly simplifies the recycling process, but it is not always used and the construction waste is taken to the landfill [7].

The most labour-intensive is the preparation of drywall waste obtained from completely destroyed buildings and structures as a result of natural disasters or military operations. In this case, the required material categories are separated from the total mass of construction waste by manual disassembly. The drywall thus obtained (figure 2, b) can have a high degree of contamination in the form of nails, screws, wires, insulation, glue, wall coverings, etc., and can be analysed for harmful impurities. Waste drywall is disposed of in two main ways: landfill and recycling. Landfill is the most common and easiest method in most countries, but there are significant problems with it. Although gypsum is a small proportion of the total waste, its disposal usually results in hydrogen sulphide emissions and higher greenhouse gas emissions [8].

Due to the huge amount of drywall waste, much research is being conducted on the rational use of gypsum isolated from it. At the Czech Technical University in Prague, the effectiveness of using drywall waste in mixtures for the production of gypsum blocks was studied [6]. Gypsum isolated from drywall, containing more than 95% $CaSO_4$, was calcined at a temperature of 1200 °C. Taking into account water coefficient, amount of foam, polypropylene microfibres and density of gypsum mixture, its thermal and strength properties were investigated. The obtained results confirmed the prospectivity of the considered direction of utilisation of drywall waste. The possibility of using such waste in the production of new gypsum drywall sheets is considered in [9, 10].

The use of powdered recycled gypsum in concrete mixes reduces carbon dioxide emissions by reducing the amount of cement. A study [11] used recycled gypsum powder to introduce more sustainable and environmentally friendly concrete production while maintaining adequate strength and durability. Studies have shown positive results for the use of gypsum powder in the agricultural industry [12].

The current drywall recycling technologies do not have any noticeable differences. They are

(*a*)

(*b*)

Figure 2. Sorted drywall: a – during construction of new buildings; b – during demolition of demolished buildings.

based on the method in which the initial drywall is sorted and loaded into a receiving hopper from where it is fed to the shredding plants. The method provides for the conversion of the entire mass of drywall into a fine-grained product by means of successive coarse, medium, fine crushing and further separation in a drum separator into gypsum component and paper.

In particular, the Turkish company Parget Makina [13] at the first stage of drywall processing uses a shredder of drywall sheets in the working chamber of which there are two shafts with disk toothed knives. The resulting mass of fragments is fed into a separator for processing drywall waste with a capacity of up to 20 t/h. The separator is made in the form of a cylindrical chamber with an inner shaft on which radially fixed destructive elements in the form of rods, blades, plates and others. The lower part of the chamber has a perforated surface for the output of the product of a given fraction.

In a number of design schemes of drywall waste recycling plants, roll crushers are used. At the first stage of coarse crushing [14], the rolls of the double-roll crusher are made with spikes that break the panel into pieces. In the next stage, the pieces are conveyed by a conveyor belt to the double roll crusher for fine crushing. A magnetic catcher can be installed along the transportation path. The crushed mass enters the drum separator, where the gypsum component is further crushed and discharged through the perforated bottom with holes of 4...25 mm. To grind waste in one stage, multi-roll crushers are installed [15], and the efficiency of grinding can be increased by giving the paired rolls different speed of rotation. Similar designs take place in [16, 17], etc.

The processing of drywall into a mixed fine-grained product is a common disadvantage of the currently used crushing and grinding equipment. The multistage processing process increases the metal intensity of the processing line, its overall dimensions, requires a significant number of handling devices. It becomes problematic qualitative separation of components, especially in the processing of contaminated boards.

A promising direction for the development of drywall processing technology is proposed to use small crushers, as well as mobile units directly on the construction site [18, 19].

The current technology is used in processing plants [20], but the urgency of the problem requires research and development of new technological schemes and small-sized efficient equipment.

Research aim is to determine the efficiency of innovative technological process of recycling of construction waste drywall into secondary raw materials with the use of small-sized vibratory jaw crusher.

2. Results

When disintegrating composite materials, one of the significant factors affecting the quality of separation of the component parts is the working surface of the executive body, interacting with the object being processed. Research on the selection of the lining surface of the jaws of a vibratory jaw crusher was carried out on a laboratory impact bench, the design and operating principle of which are described in [21].

The transformed impact unit (figure 3, a) includes the lower 1 lining plate, rigidly fixed on a massive base 2 and the upper 3 lining plate, fixed on the mounting disk 4 of the pendulum 5. A replaceable load 6 is attached to the top of the disk. The test sample of drywall 7 (figure 3, b) is placed on the lower lining plate 1. The working plane of the upper lining plate 3, by means of rotating mechanisms (not shown in the figures), is installed parallel to the opposite surface of the drywall sample. This ensures contact of interacting elements over the entire area of the connector at the moment of impact. The impact energy for all studied samples was assumed to be 35; 55 and 75 J.

The effectiveness of the lining plate was assessed by the percentage of destroyed gypsum in the test drywall sample per blow.

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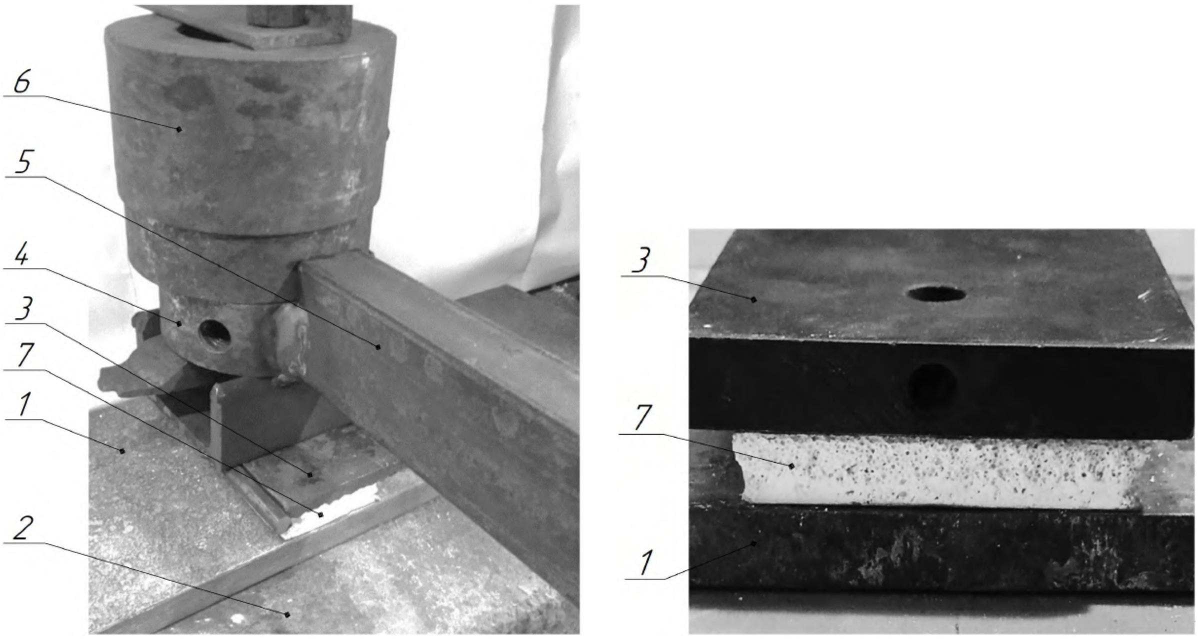


(*a*) (*b*)

Figure 3. Arrangement of elements of the impact unit in statics: a – impact unit; b – initial installation of drywall sample.

When impacted by the smooth surface of the lining plate (figure 3, b), the sample practically retains its original shape. Minor damage to the gypsum layer occurs at the ends and increases with increasing impact energy (figure 4, curve 1), however, the central part of the layer opens extremely slowly. The use of such a surface when crushing drywall is impractical.

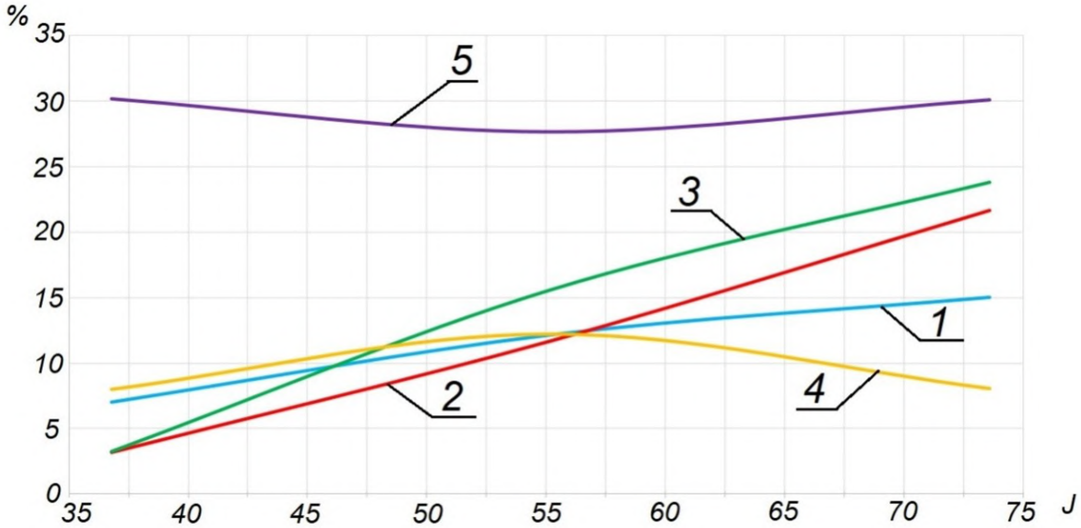


Figure 4. Dependence of the destruction of the gypsum layer on the impact energy for the shape of the working surface of the lining plates: 1 – smooth top/smooth bottom; 2 – pyramidal upper/smooth bottom; 3 – prismatic top/smooth bottom; 4 – wavy top/smooth bottom; 5 – wavy top/wavy bottom.

In order to influence the crushing process of pinpoint impacts, the working surface of the lining plate (figure 5) is made in the form of pyramidal protrusions with a height of 2 mm and a pitch of 5 mm.

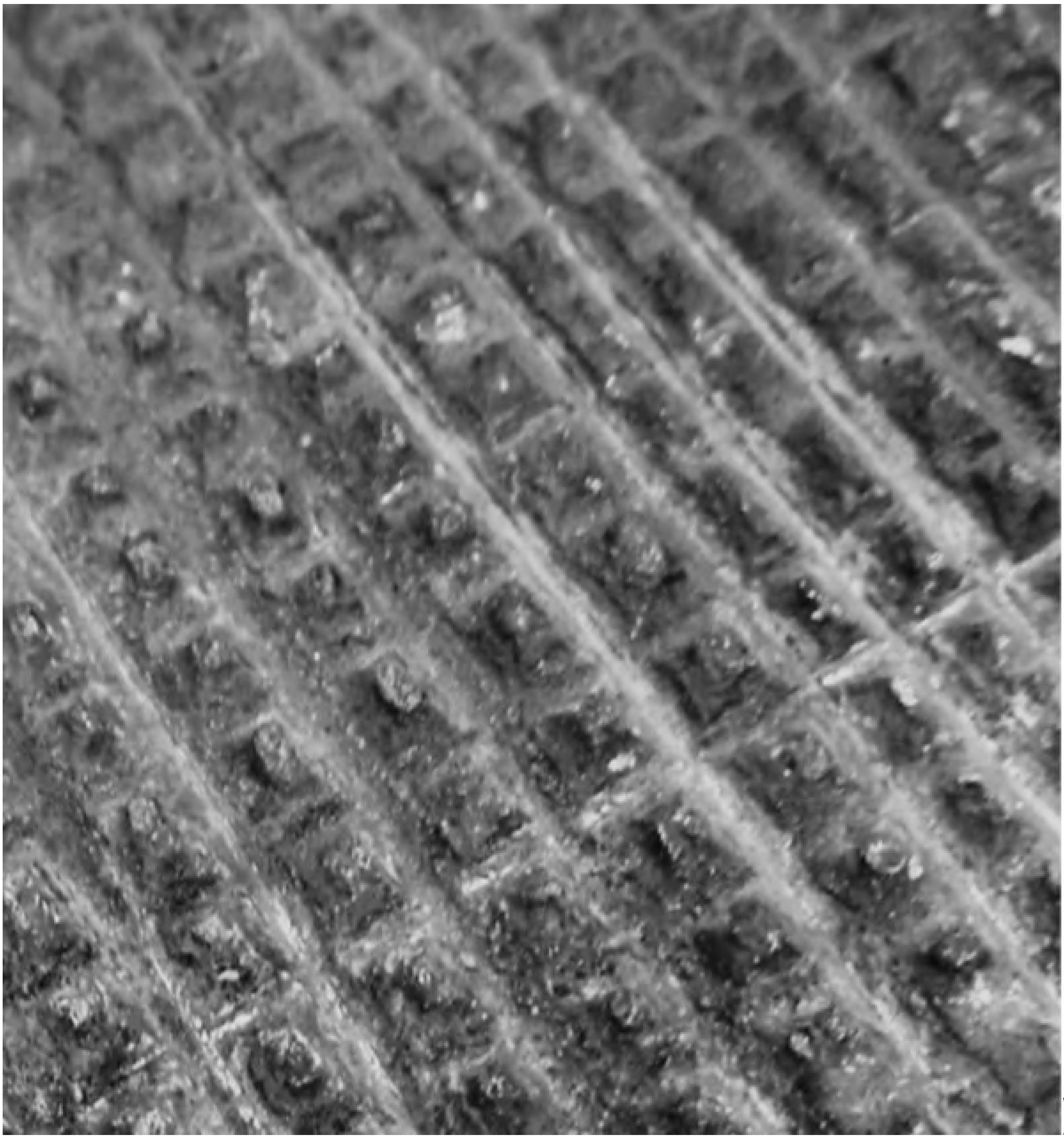


Figure 5. Pyramid surface of the lining plate.

Analysis of the obtained results shows that for all accepted values of the impact load, the qualitative picture of the destruction of the samples is preserved. With increasing impact energy, the yield of destroyed gypsum fractions increases (figure 4, curve 2). The top plate of cardboard (figure 6) is separated and the top plane of the gypsum layer is exposed, loosened by the protrusions of the lining plate, which can significantly improve the process of gypsum separation in the subsequent crushing stage.

Figure 6. Crushed drywall: 1 – gypsum; 2 – cardboard.

During the research, the force impact on drywall by a lining surface made by a set of triangular prisms was considered (figure 7).

The side ribs of the prisms can practically be located at any angle to the direction of movement of the material in the crushing chamber. At the impact stand, we limited ourselves to installing lining plates with the side ribs of the prism directed perpendicular to the longitudinal side surface of the drywall sample.

The process of interaction of the lining surface with the sample can be divided into several phases. Initially, at the moment of contact, the cardboard stretches between the penetrating side edges and simultaneous compression of the gypsum located in this gap occurs. As a result of the relative displacement, there is a lack of rigid connection between the components of the drywall and the formation of individual elements. The subsequent impact of the lining on the sample leads to rupture of the cardboard along the length of the side ribs (figure 8) and the formation of cardboard strips, the width of which corresponds to the distance between adjacent side ribs. The upper surface of the gypsum layer becomes free and displays the profile of the lining plate, has areas of compaction under the side ribs and loosening under the side edges. With a single impact, the prismatic lining in combination with the smooth surface of the lower lining showed (figure 4, curve 3) the highest yield of the destroyed fraction. However, many relatively small

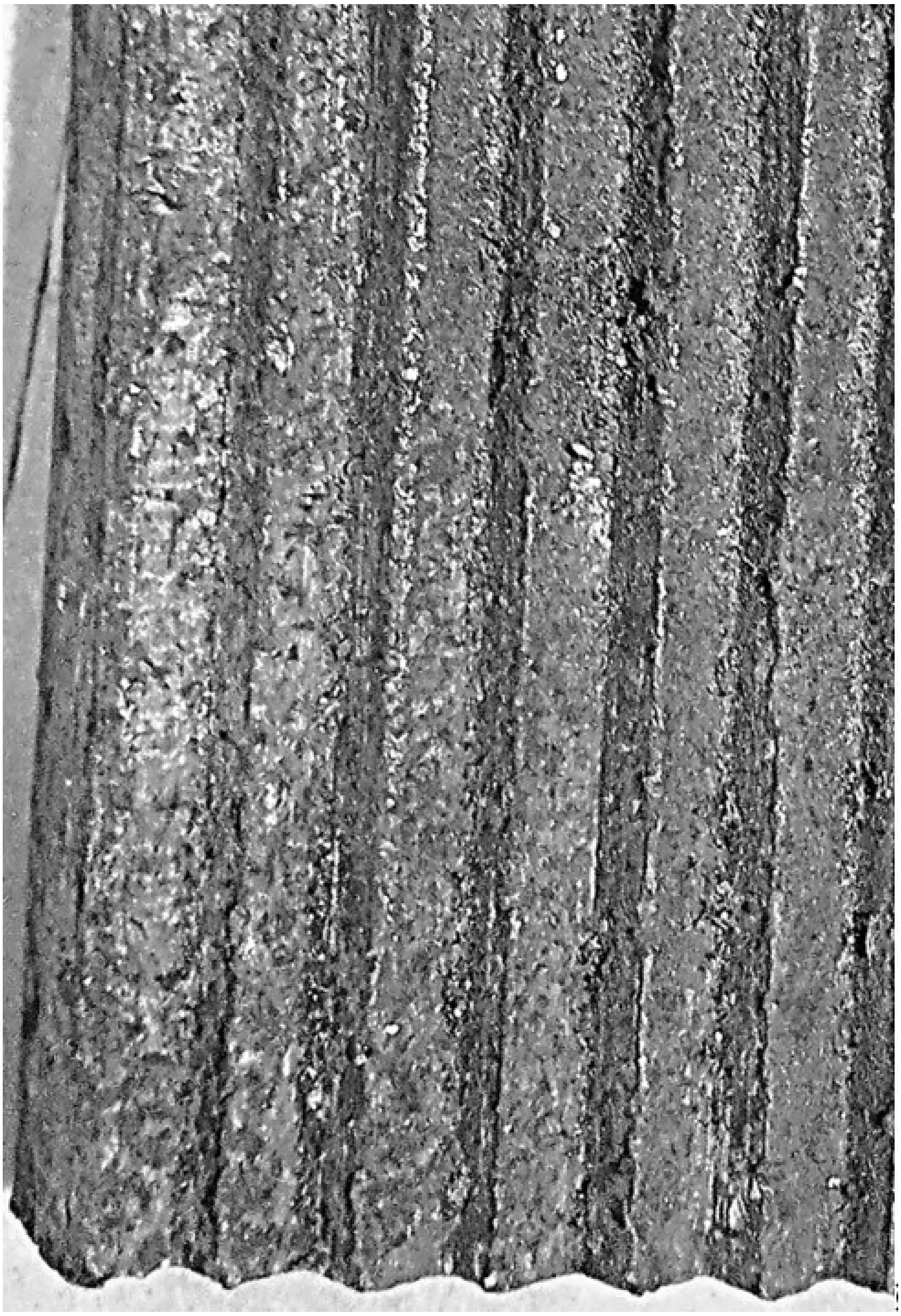


Figure 7. Prismatic surface profile of the lining plate.

cardboard strips under high-frequency impact loading will transform into a fine-grained material and create a problem in separating it from the gypsum component.

The oval surface profile of the lining plate (figure 9) was considered for several options. When installing a sample of drywall on a flat base, an ambiguous result was obtained. The curve (figure 4, curve 4), describing the amount of destroyed gypsum, has a maximum. This is

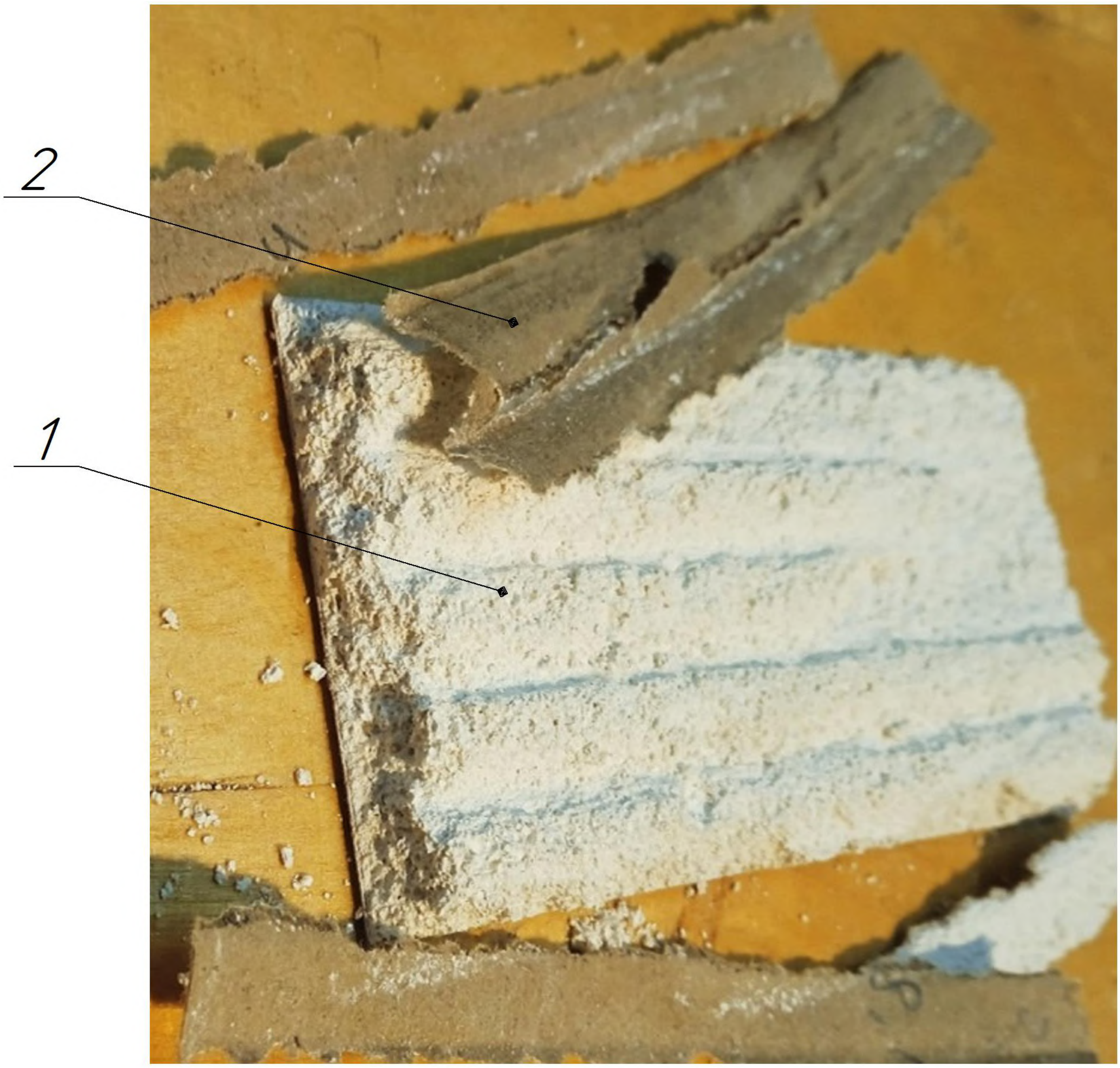


Figure 8. Crushed drywall: 1 – gypsum; 2 – cardboard.

probably due to the rather large contact area of the lining plate with the surface of the sample and the formation of compressed gypsum sections.

The working surface of the lower jaw of a vibratory jaw crusher can be equipped with a different profile. One of the combinations, the mutually perpendicular arrangement of ovals (figure 10), gave a significant increase in the amount of destroyed gypsum (figure 4, curve 5).

The results obtained on the impact stand show a significant dependence of the effective destruction of the gypsum layer of drywall on the profile of the lining plates.

Crushing of drywall was carried out on a laboratory sample of a vibratory jaw crusher with an inclined chamber [22]. This type of crusher has a pronounced impact nature of the application of load to the crushed material, and has the advantages of jaw and rotary crushers. Having a large set of adjustable parameters (frequency, amplitude of vibrations and mass of the jaws, size of the unloading gap, profile of the working surface of the jaws, grip angle, etc.), the process of destruction of the material is effectively controlled. In general, the design diagram of the

Figure 9. Oval surface profile of the lining plate.

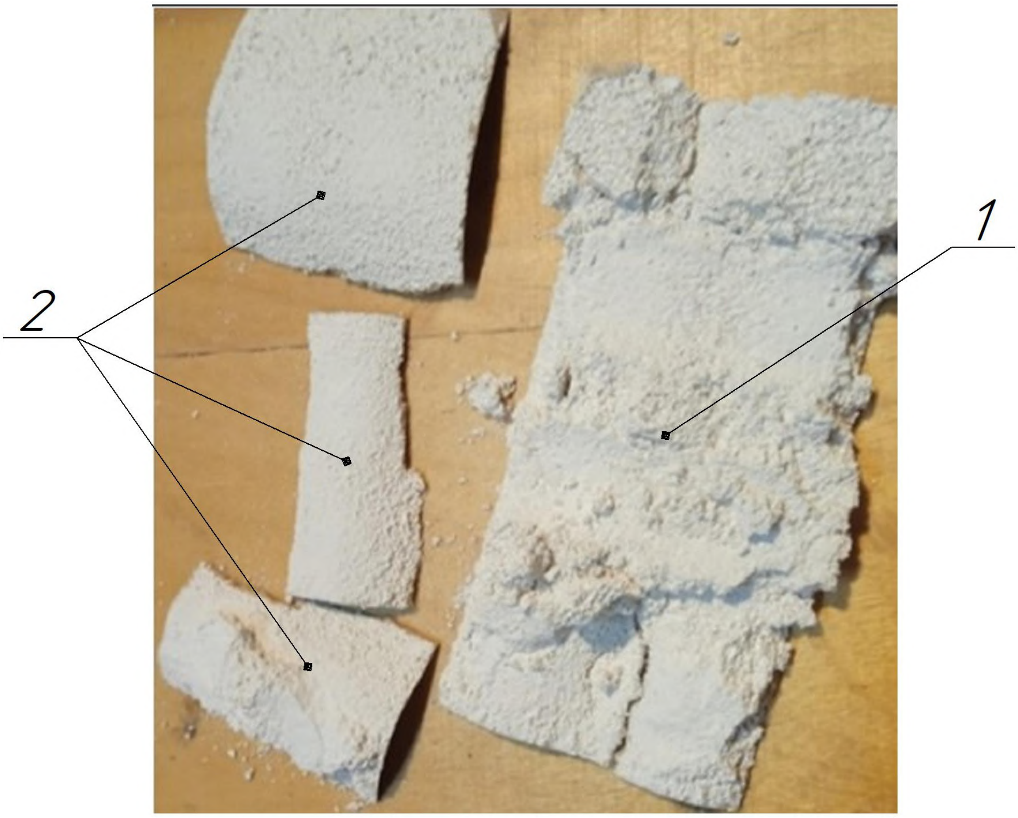
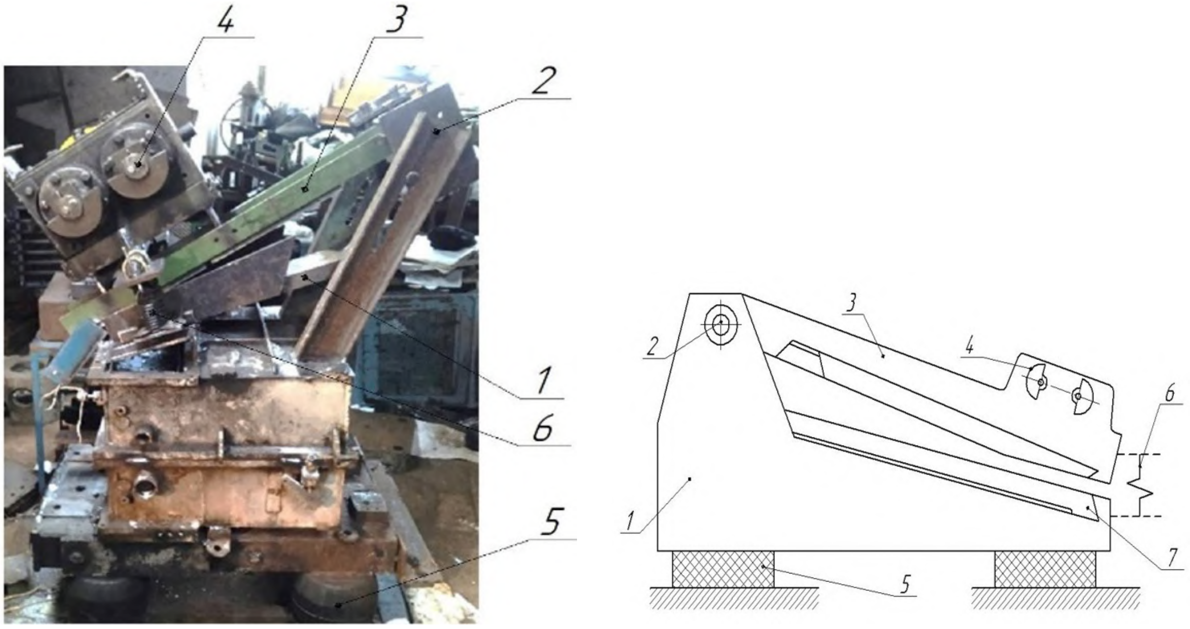


Figure 10. Crushed drywall: 1 – gypsum; 2 – cardboard.

vibratory crusher represents an oscillatory system in which vibrations with a frequency of 16 – 32 Hz are transmitted to the jaws.

A vibratory jaw crusher with an inclined crushing chamber (figure 11) includes a passive (lower) crushing jaw 1 with a liner plate 7, mounted on elastic elements 5 and simultaneously serving as a 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 oscillations. The vibrations of the jaws are generated by a two-shaft inertial vibration exciter 4. The destruction of the material occurs in the crushing chamber formed by the working surfaces of the passive 1 and active 2 jaws. The design feature of the crusher allows loading of the source material and unloading of the crushed product in a horizontal plane, which is especially important when processing sheet material. The working surface of the lower jaw is made smooth, the surface of the upper jaw is oval with the longitudinal axis of the ovals located perpendicular to the movement of the strip. The vibration frequency of the jaws was 16.7 Hz, the width of the unloading gap was set to 0 mm and 10 mm.



(a) (b)

Figure 11. Vibrating jaw crusher with an inclined crushing chamber: a – general view of the crusher, b – structural diagram.

Strips of Knauf Blue drywall, 12.5 mm thick and 130 mm wide, identical to those studied on the impact stand, were crushed. Figure 12 shows a typical view of drywall coming out of the crushing chamber. There is a slight residual gypsum deposit on the inside of unbroken cardboard plates, and the gypsum core has a fairly high degree of crushing. Thus, the original composite material is divided into three components, which represent secondary raw materials.

The resulting form of the crushed product allows for fairly simple separation on the sieving surface. The qualitative characteristics of the material after sieving are presented in figure 13, the quantitative characteristics – in figure 14.

Fraction 0 – 200 (figure 14) after calcination restores the properties of gypsum and can be used in the production of drywall, building materials, etc. Larger fractions, as finished commercial products, are used in agriculture, cement production, landscape design, etc. This indicates on the feasibility of recycling drywall waste at the site of its generation, which will make it possible

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Figure 12. Drywall after high-frequency force loading: 1 – bottom plate, 2 – top plate, 3 – gypsum.

Figure 13. Crushed gypsum component of drywall.

to both obtain marketable products and reduce transportation costs, relieve garbage dump, improve the environment and preserve mineral resources.

The graphical dependence (figure 14) demonstrates the qualitative similarity of the granulometric curves at different widths of the unloading gap. In quantitative terms, the output of individual classes differs from each other. This indicates the possibility of changing the content

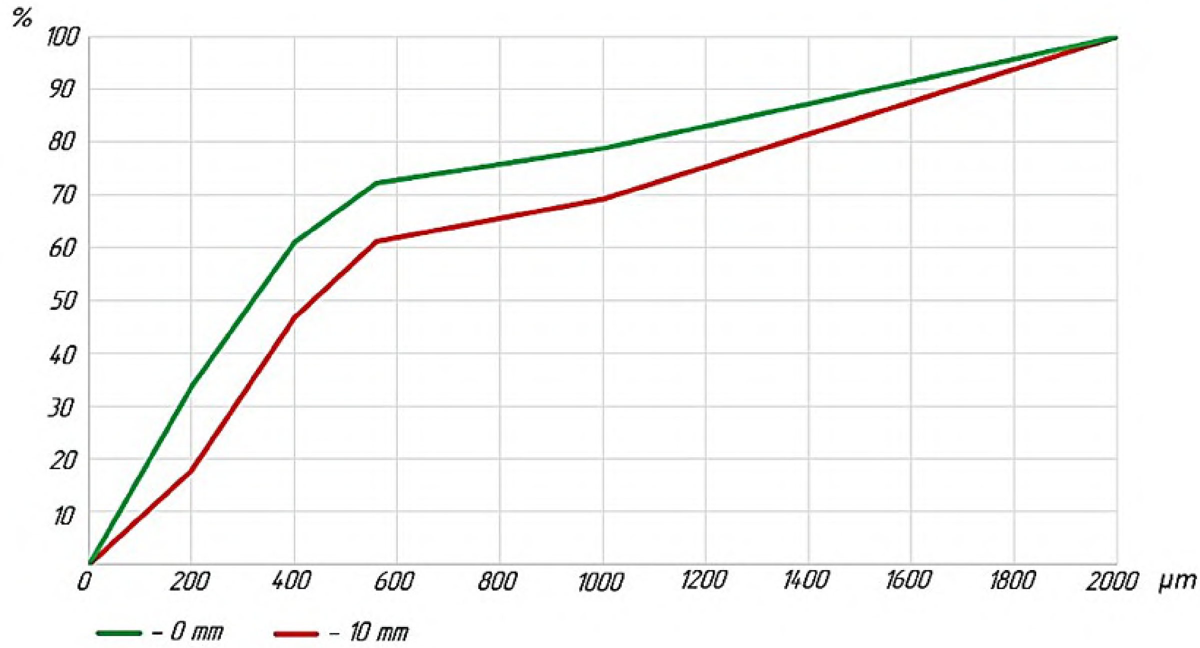

Figure 14. Characteristics of crushed gypsum size.

of the required size class in the finished product and preparing the material with the specified parameters.

The process of crushing contaminated drywall is similar to that outlined above. When using a vibratory jaw crusher with an inclined crushing chamber, most of the crushed gypsum component located inside the panel is clean material. Contaminated material is generated from the end surfaces of the panel and from the outer planes of the cardboard plates. The main part of plate contamination (paint, glue, wallpaper, varnish, etc.) remains almost unchanged in the considered crushing method. In this connection, in comparison with existing methods of drywall processing, the insignificant percentage of contamination allows direct use of the obtained gypsum component in agrarian and some other industries.

3. Conclusion

1. The analysis of literature sources indicates the rapid growth of drywall waste, environmental hazard when throwing it to the landfill and the possibility of recycling, which substantiates the relevance and necessity of research, development of innovative technologies implemented in the created efficient equipment.
2. A huge number of destroyed buildings is associated with the need to create landfills for storage of construction waste and its subsequent processing. The conducted research has shown that a significant part of waste, in particular drywall, can be successfully processed in a small-sized vibratory jaw crusher with an inclined crushing chamber. Insignificant dimensions and small occupied area predetermine the installation of the crusher directly at the place of formation of construction waste drywall in the process of its sorting. Obtaining a marketable product reduces the load on landfills, reduces transportation costs, improves the environment and conserves mineral resources.
3. In the process of researches on drywall crushing on vibratory jaw crusher with an inclined crushing chamber the modes at which separation of components for one pass of drywall through the crushing chamber is carried out are received, that allows to create lines on

processing of drywall with one stage of crushing and reduction of their metal consumption and dimensions.

4. On the impact stand the research on force impact on the flat surface of drywall was carried out by the impactor having a flank in the form of: pyramidal protrusions, a set of three-sided prisms, a set of oval protrusions and a plane. The obtained results show a significant dependence of the effective destruction of the gypsum layer of drywall on the profile of lining boards, with the greatest effect observed with oval protrusions, the least with a flat impactor.
5. The vibratory jaw crusher has a sufficient number of parameters that control the crushing process: frequency and amplitude of vibrations of the jaws, the magnitude and direction of the disturbing force, the mass of the jaws, the size of the unloading gap, the rigidity of the elastic elements, the profile of the working surface of the jaws, the grip angle, the angle of inclination of the transporting surface, which allows you to significantly increase the obtained indicators based on additional research.

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Utilization of vegetative waste from green infrastructure of cities "in-situ"

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Utilization of vegetative waste from green infrastructure of cities "in-situ"

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Abstract. Taking into account the need to provide the city's population with green areas in accordance with the European program "Green City", there is a problem of the formation of large volumes of plant residues that need to be utilized. At the same time, the cultivation of green infrastructure elements on urban soils requires of fertilizer. The analysis of existing systems for the management of fallen leaves in different countries, including Ukraine, was carried out and the creation of a municipal infrastructure for the disposal of in-situ organic waste of plant origin in the context of the circular economy was proposed. The author's technology for the creation of municipal infrastructure for the disposal of organic waste of plant origin for different urban landscapes. The effectiveness of using plant waste to form the initial substrate for the creation of composts and vermicomposts was investigated. The volumes of phytomass formation from fallen leaves in the green zones of administrative districts and the city as a whole, as well as in household plots with different vegetation composition were calculated. On the basis of the data obtained, a SWOT analysis was made of the implementation of the program utilization of plant waste.

1. Introduction

The relevance of the study is due to the need for ecosystem management in the disposal of urban organic waste as an important cluster of the Smart City concept and Green City. Ukrainian cities are gradually moving towards the implementation of the principles underlying the EBRD Green City program [1]. The program provides for the creation of new and revitalization of existing green areas in cities, bringing the provision of urban green spaces to 50 m^2 /1 person. This is the rate of urban greening recommended by the World Health Organization. During the growing season of green spaces and especially at the end of it in autumn, a large amount of plant organic phytomass is created, which needs to be utilized. Thus, the collected leaves in most cases fall into containers with household waste and are taken to landfills or burned in places of accumulation.

Burning of vegetative organic waste is a violation of Ukrainian legislation, namely: Article 50 of the Constitution of Ukraine; Articles 9, 12 of the Law of Ukraine "On Protection of the Natural Environment"; Article 16 of the Law of Ukraine "On Protection of Atmospheric

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Air"; paragraphs 3.6.14, 3.7.4 "Rules for the maintenance of residential buildings and adjacent territories"; paragraphs 3.6, 6.4.2 "Rules for the maintenance of green spaces in cities and other settlements"; the Law of Ukraine "On landscaping in settlements".

It is inexpedient to dispose of plant organic waste to landfills, thus significantly increasing the burden on public utilities and the area allocated for waste disposal.

As an alternative to these methods of disposal of fallen leaves and other plant residues is composting, vermicomposting or biodynamics. Our study is devoted to these issues. Its purpose is to assess the opportunities and risks of using composting and vermicomposting for the disposal of plant waste in urban landscapes.

2. Literature review

According to the UNEP, important areas of green economy development are, in particular, the utilization and recycling of domestic and industrial waste, greening of the urban environment. On the one hand, cities are the main polluters of the environment, and on the other hand, they have a powerful potential for implementing the green growth model.

Among the leaders in the development and implementation of new policies is the European Union, where environmental policy is one of the development priorities. This direction is enshrined in the following EU strategic documents: "Europe 2020: A Strategy for Smart, Sustainable and Inclusive Growth" and the Resource Efficiency Roadmap [2]. The EU Sustainable Development Strategy "Europe 2020" aims to promote sustainable growth by developing a more resource efficient, green and competitive economy. In 2011, the Roadmap for the transition to a low carbon EU Society by 2050 was adopted [3, 4].

In its publication "Sustainable Financing and Policy Models for Municipal Composting", the World Bank considers composting as a strategy for organic waste management and states that organic waste management is a growing global concern as cities experience increasing waste generation and the associated climate impact. Composting is a sustainable solution for managing organics that has the potential to be inexpensive and require less technical capacity than alternative treatment methods. Composting potentially reduces waste management costs as it avoids landfill fees, extends the life of the waste and reduces transportation costs. World Bank experts emphasize that there is no single model that can be applied to all cities. There is a need to develop several models that will differ in approaches to waste collection, composting technologies, scaling, and distribution depending on the characteristics of the city [5].

The European Bank for Reconstruction and Development, within the framework of the project to support investments in sustainable municipal solid waste management and recycling in Ukraine, has developed a Solid Waste Management Strategy called "Changing our Behaviour" for the period 2017-2030. The approach of the Strategy "Changing our Behaviour" means transforming the attitude in Ukraine towards waste in favour of considering it as a valuable resource to be managed, rather than a problem to be solved [6].

The difference between the situation with waste in Ukraine compared to other developed countries is the large volumes of waste generation and the lack of waste management infrastructure. At the same time, the availability of such infrastructure is an indispensable feature of all economies of developed countries [7].

The total area of green spaces in the built-up part of Kyiv is 16.8 thousand hectares. On average, 260 trees grow on one hectare. When shedding, the weight of 1 square meter of leaf ball in the moistened state is 100 g. The weight of leaves of one middle-aged tree is 35 kg, young – about 10 kg (young trees occupy 40 % of the total area of green spaces – Obolon, Troyeshchyna, Teremky and other residential areas). The weight of 1 cubic meter of wet leaves is 300 kg. The total weight of leaf mass in medieval plantations per 1 hectare is 9.1 tons; young plantations – 2.6 tons. The total weight of all leaf mass of the capital is about 100-110 thousand tons [8].

Nutritious compost substrate has a higher (2-3 times or more) content of organic matter, macro- and microelements, mineral and organic colloids in comparison with soil. Its application allows to improve the agronomic properties of the topsoil for 5-6 years, optimizes the agrophysical and agrochemical parameters of the soil, improves the use of nutrients by plants, optimizes water consumption.

The purpose of the work is to substantiate the creation of municipal infrastructure for the utilization of organic waste of plant origin "in-sity" for various urban landscapes.

3. Methods

An analysis of the methods presented in several specialized publications [9–13] made it possible to determine the most optimal one, since it takes into account the entry of carbon into the soil, fixed in the form of humus from the organic matter of plant residues.

The estimated calculation of plant residues was carried out according to the method of calculating the balance of humus and organic fertilizer rates to ensure its deficit-free content in chernozem soils, which was developed by Chesnyak and Zinchenko at the ESC "O.N. Sokolovsky Institute of Soil Science and Agrochemistry". According to this method, the profitable item of the humus balance includes the inflow of carbon into the soil, fixed in the form of humus from organic matter of plant residues and organic fertilizers. Other sources of humus replenishment in the soil, such as seeds and atmospheric carbon dioxide sequestered by blue-green algae, are not large and are not taken into account [14].

The mass of plant residues is determined by means of regression equations on the yield of the main product (c/ha) as the sum of surface and root plant residues. In particular, the mass of surface plant residues of potatoes, vegetables and melons is determined by the following regression equation:

$$Z = 0.068Y + 0.5X, \tag{1}$$

mass of root plant residues is determined by the regression equation:

$$X = 0.07Y + 8.0 \tag{2}$$

When calculating the amount of newly created humus from plant residues, the corresponding humification coefficients are used. They show how much newly created humus is obtained from decomposing plant residues. In particular, the humification coefficient of plant residues for potatoes, vegetables and melons is 0.13.

4. Results and discussion

Among the modern methods of utilization of plant organic residues, in particular processing into fuel briquettes and pellets, biogas production, composting to obtain a nutrient substrate, utilization by composting and vermicomposting of organic plant waste is the most environmentally friendly and economically feasible approach.

At the same time, the dominant way of handling household waste in Ukraine remains its removal and disposal in landfills and dumps. In 2016, only 0.003 % of organic waste was composted in Ukraine [7].

In addition, spontaneous dumps of plant residues and fallen leaves are often formed in local areas of public territories in rural urban and suburban areas. The reason for this situation is that local residents in response to the ban on burning leaves generally refuse to further dispose of them. Of course, a significant drawback in working with the population is the lack of environmental education and the formation of basic environmental knowledge.

A survey of residents of settlements in Kharkiv oblast revealed an insufficiently high level of competence among owners of private estates in the field of environmental management. In particular, every second respondent could not give the correct answer to the question about the definition of the terms “humus”, “soil pH”, “nutrients” [15].

The main organizing role in changes related to waste management in Ukraine belongs to local authorities. They are obliged to ensure the continuous improvement of the physical and social environment in which their communities live. Therefore, it is advisable for land management departments, departments of communal property and ecology of city (settlement, village) councils to actively implement measures with the participation of ecologists, agronomists to teach composting technologies, etc.

Monitoring and control of measures to implement the National Waste Management Strategy in Ukraine until 2030 is carried out, in particular, by such an indicator as “the number of composting points in households” [7]. It is necessary to stimulate the introduction of composting technologies by owners of private estates, in particular by providing compost boxes for rent or free of charge at the expense of local budgets. The problem of illegal waste disposal can be solved by establishing financial sanctions. The funds received from compensations paid for the deterioration of the ecological condition of soils by unscrupulous land users can serve as a source of funding for incentive measures.

The Program of in-situ municipal utilization of plant waste developed by the authors aims to adjust the strategy of organic waste management in public urban, settlement, rural areas, as well as to focus on the formation of a culture of environmental management among owners of private estates who use their land for horticulture and gardening. The practical value of the Program lies in the use of ecosystem management in the disposal of urban organic waste in the context of the implementation of the circular economy concept for the Smart City green cluster. The novelty of the program is the development of in-situ recycling technology, i.e. on-site recycling of plant organic waste (plant residues, branches, leaves, grass), without their transportation by composting or vermicomposting.

Currently, there are no completed projects in Ukraine to create municipal infrastructure for in-situ disposal of organic waste of plant origin. The proposed technology belongs to one of the eight clusters of critical factors, namely, the green cluster, which form the content of smart city initiatives. The program has clear and realistic goals. The strength of the program is high environmental and economic efficiency, a wide range of stakeholders interested in the project results, involvement of the end user (city residents) in the project.

Disposal by composting and vermicomposting of organic plant waste is the most environmentally friendly and economically feasible approach. Composting is one of the models of waste management at the municipal level. The estimated calculation carried out by the authors according to the methodology of Chesnyak and Zinchenko [14] shows that in household plots where potatoes, vegetables, melons are grown, 4.0-4.5 t/ha of plant residues that need composting accumulate during the growing season.

Within the framework of research conducted by the Department of Environmental Monitoring and Conservation in households in Kharkiv and Kirovohrad regions, whose household plots were occupied not only by a vegetable garden, but also by a productive fruit-bearing garden, mixborders with perennial plants, lawn, formed hedges, the mass of plant residues during the growing season reached 10 t/ha.

In Ukraine, within the family-individual household sector of rural areas, the land use of household plots and personal peasant farms prevails, in particular, household plots of citizens in rural areas alone account for about 10 million households with a total area of almost 1.5 million hectares [6]. The average size of such plots is: width – 10-40 m, length – 20-100 m [7].

That is, composting as a strategy of organic waste management for balanced nature management on household plots with the cultivation of fruit, vegetable, ornamental crops have the potential to create up to 2 million tons of humus only at the expense of households in rural areas.

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An important factor affecting the intensity of the composting process is the ratio of carbon and nitrogen. The most favorable C:N ratio for intensive microbiological processes is 25:1. It is generally accepted that if crop residues have a high carbon content, the nitrogen content can be compensated with a nitrogen fertilizer of 0.5 to 1 %, which accelerates the composting process.

If only nitrogen fertilizers are used, crop residues become a place for the development of all indigenous microflora, including pathogens. This means that they also activate pathogenic organisms, Fusarium, rot, mold, etc. When the destructor is added, the soil is populated with saprophytic microorganisms in high concentration, which displace pathogens. This happens both through direct competition for habitat and nutrients, and through the synthesis of antibiotic compounds that inhibit the development of pathogens.

Modern microbiological destructors of Ukrainian production for the controlled decomposition of plant residues contain strains of *Bacillus, Paenibacillus polymyxa, Azotobacter, Enterobacter, Enterococcus, Agrobacterium*, strains of fungi of the genus Trichoderma. These preparations for accelerated decomposition of fallen leaves directly on the territory of the garden, park: it is enough to treat with a working solution in a concentration of 2.0 l/ha during the leaf fall, the cost of one liter of the preparation is 4.3 €.

Expected effect: effective decomposition of leaves, reduction of soil toxicity, improvement of soil structure, increased availability of nutrients, biocontrol of pathogens. The latter function is especially important for improving the conditions of growth and development of the main tree species of urban landscaping, in particular, maples, lindens, chestnuts, which have a high level of infection with phytopathogenic fungi.

The use of such effective microbiological preparations is safe for human and animal health, solves the problem of creating high-quality composts both in rural and urban areas. They activate the natural forces of plants, help plants survive adverse biotic and abiotic conditions, preserve their decorative qualities and the natural beauty of a small garden or a large park.

Previous studies have found that such species as *Fraxinus excelsior L., Tilia cordata, Tilia platyphyllos*, representatives of the genera *Populus L., Betula L., Sambucus nigra L., Hedera helix L., Parthenocissus quinquefolia (L.)* Planch, species and varieties of *Vitis L.* respond well to the improvement of nitrogen nutrition in urban ecosystems by the state of morphological organs and crown habitat [16].That is, these species actively accumulate nitrogen compounds.

Therefore, it is appropriate to form the green infrastructure of the city using plant species and cultivars with high nitrogen content in the leaves, which will contribute to intensive microbiological processes during composting. According to the authors, such cultivars as *Catalpa bignonioides, Catalpa ovata, Morus alba, Malus niedzwetzkyana, Malus x floribunda, Malus hybridus, Crataegus laevigata* meet such requirements.

Vermicomposting is a system of organizational and technological measures with the use of vermiculture – populations of dung worms together with accompanying heterotrophic organisms in a specific organic substrate, Vermicomposts – products of processing of organic mass by earthworms and microorganisms. The processing of organic waste produces a valuable organic fertilizer – vermicompost. The production of biohumus is based on the ability of earthworms to use organic residues, transform them in the intestines and excrete them in the form of coprolites.

The best samples of vermicompost contain several billion cells of microorganisms in 1 g, which is much more than in manure samples (about 150-360 million cells). Biohumus has a high enzymatic activity. Its organic matter contains a significant amount of humic acids (Chc = 31.7-41.2 %) and less fulvic acids (Cfc = 22.3-34.85). In humic acids the most valuable fraction prevails – calcium humates (43.3-47.6 %). The presence in vermicompost of fulvate-humate type of humus (Cgc: Cfc = 1.18-1.42) contributes to the formation of agronomically valuable soil structure [17, 18]. Nutrients in the process of interaction with organic acids form complex complex compounds, so they are reliably preserved from leaching, slowly dissolve in water and provide plant nutrition for a long time (at least 2-3 years).

Biohumus has a multifaceted positive effect on agrochemical, physicochemical and biological properties of the soil. It contains a complex of nutrients and therefore can be used for all crops, but is especially useful for those that require nutrients in concentrated form, balanced in chemical composition.

Worms release calcium from the substrate and thereby reduce the acidity of the environment. The coefficient of substrate humification is 15-25 %, while for manure it is about 10 %. As a result of intensive fermentation, biohumus is enriched with a large number of biologically active substances (auxins, heteroauxins, etc.), which significantly reduce the stress of plants, especially seedlings when planting in the soil, increase its survival rate, accelerate seed germination, increase plant resistance to diseases, affect their growth, development and thereby contribute to obtaining early products of high biological quality suitable for long-term storage. Biohumus also has other valuable properties: high moisture capacity, moisture resistance, hydrophilicity, mechanical strength, does not contain weed seeds. It is able to retain up to 70 % of water and is 15-20 times more effective than any organic fertilizer [17, 18].

The agrochemical properties of the average sample of vermicompost are as follows acidity (pH) – 6.5-7.2, dry organic matter content – 40-60 %, humus – 10-12 %, total nitrogen – 0.9-3.0%, phosphorus (P_2O_5) – 1.3-2.5 %, potassium (K_20) – 1.5-2.5 %, calcium – 4.5-8.0 %, magnesium – 0.5-2.3 %; iron – 0.2-2.5 %, copper – 3.5-5.1 mg/kg; manganese – 60-80 mg/kg; zinc – 28-35 mg/kg; humidity – 40-50 %; bacterial form – up to 20 trillion colonies in 1 g of vermicompost [17, 18].

Nutrients are in organic form, so they are reliably preserved from leaching. Due to the decomposition of vermicompost by microorganisms, macro- and microelements are released, plants are provided with carbohydrates necessary for photosynthesis. When applying vermicompost, which is characterized by high buffering capacity, an excessive concentration of salts is not formed in the soil solution, which can be traced in the case of high doses of mineral fertilizers.

Vermicomposts are especially valuable due to humic acids, the content of which ranges from 5.6 to 17.5 % in terms of dry matter. In addition to decomposed waste, vermicomposts also contain a certain amount of dead worms, which also increases their value.

The quality of biohumus is assessed according to the international standard, which sets the following requirements: humidity – 30-40 %; organic matter – 20-30 %; water-soluble salts – 0.5 %; pH – 6.5-7.5; total nitrogen – not less than 1.6 %; P_2O_5 – 1.2-1.5 %; K_2O – 11-12 %; Cu – 1 %; Mg – 1 %; Ca – 4 % [17]. Biohumus should not contain substances that are not biologically processed (polymers, stone, glass), plants capable of reproduction. The nutrients of vermicompost dissolve slowly in water, and therefore can nourish plants for a long time. In granular humus fertilizers, the humus content is 4-8 times higher than in manure and compost.

To obtain biohumus from fallen leaves, a population of special worms is used. The optimal density of worms in one bed is 50-100 thousand adults and young individuals, as well as cocoons with eggs. It is established that the productivity of vermiculture depends on the density of the bed. If the density is excessive, the excitement of worms increases and stress caused by overpopulation occurs, which negatively affects their reproduction. At low density, the productivity of worms and the yield of vermicompost also decreases. For breeding queen worms, standard beds are used, the population density of which ranges from 1.5-2.0 to 10-12 thousand individuals/m^2 [17].

Knowing the number of beds, the approximate number of worms in them, the average composition of the population by age groups (young – 60.1 %, adults – 21.8, cocoons – 18.1%), in each case it is possible to calculate the mass of the required feed (or feeding). The substrate for worms is fed with organic matter, including household and other waste, to which solid organic components – fillers – are added in various proportions to create a loose structure. They can be tree bark, leaves (except fresh needles), etc. About 1000 kg/year of substrate is required per

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100 thousand worms [17].

There are special requirements to the structure of the substrate and its chemical parameters: its humidity should be 70-80 %, it should not contain non-decomposable objects (stones, metal, glass, etc.), have a neutral reaction of the medium (optimal pH 6.8-7.2) and the content of iron oxides should not exceed 10 %.

The nutrient substrate should be of semi-liquid consistency, well crushed, as the largest particles that can be swallowed by the Californian worm are up to 1 mm in size. It is believed that the worms eat food in an amount equal to their body weight (about 1 g); 40 % of the food is absorbed, and 60 % is excreted as coprolites.

The prepared substrate undergoes a fermentation stage, during which eggs and larvae of helminths, as well as weed seeds are killed. Fermentation can be carried out both in natural and accelerated mode. In natural mode, the process lasts 6-7 months depending on the type of organic waste, and in accelerated mode – 1-3 months. To ensure the accelerated mode of fermentation, organic waste is piled in heaps, which are then supplied with hot steam at a temperature of 60 °C through pipes.

The substrate, which does not self-heat, is laid out in a layer 20-30 cm thick and 1-1.6 m wide, moistened to 70-80 % of the total moisture capacity and kept for 10-15 days. After that, it is populated with worms at the rate of 1.5-2.5 thousand individuals/m^2 [17, 18]. To preserve moisture, the substrate is covered with chopped straw or burlap. In winter, it is desirable to keep the worms in a closed warm room at a temperature not lower than +10 °C, because at a temperature of +7 °C they fall into a state of anabiosis. The best feed for them in winter is manure containing at least 20 % straw.

The vermicomposting method can be successfully used for processing organic waste on individual plots. To do this, the waste is collected in a pile, moistened and left to rot. After 1-1.5 months, when the self-heating process is over, the accumulated mass is populated with worms (at the rate of about 1 thousand individuals/m^2). After 3-4 months (depending on the quality of the substrate and climatic conditions) the compost is ready. Organic matter to be vermicultured should contain easily digestible carbohydrates and fiber in an amount of at least 20-25 %.

At the experimental site of the Uman National University of Horticulture, the suitability of fallen leaves (on the example of hazel tree) as a filler for vermicompost was evaluated, because one of the areas of work on the utilization of fallen leaves is its use as an integral part of the nutrient medium for vermiculture [19].

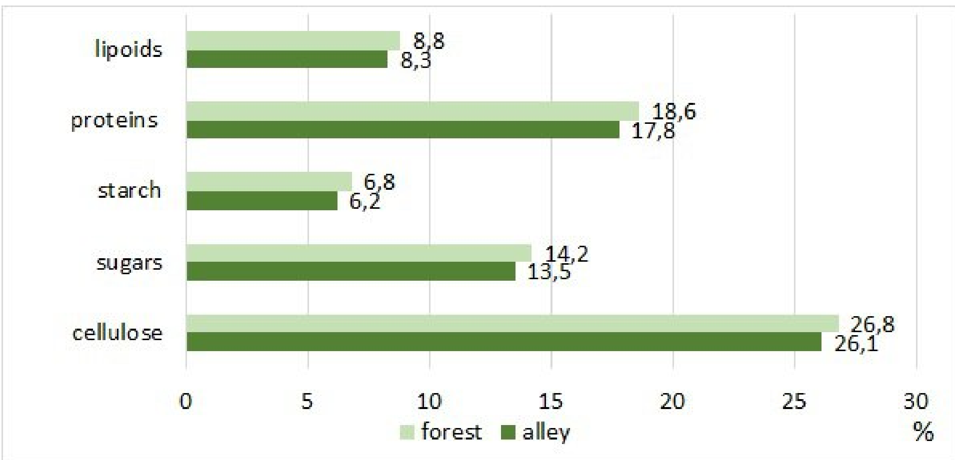

Figure 1. The proportion of organic substances in the absolutely dry mass of tree hazel leaves.

Table 1. Accumulation of fallen leaves in the administrative districts of the Kharkiv city.

Administrative district	Area, ha	Area of GI, ha	The area from which fallen leaves are collected, ha	Mass of fallen leaves,tons
Shevchenkivskyi	4418.44	2241.45	159.3	1449.2
Kyivskyi	4569.45	1001.7	53.7	488.2
Slobidskyi	2434.24	169.4	21.3	193.8
Kholodnohirskyi	3211.32	181.5	29.7	270.3
Saltivskyi	2401.24	68.3	49.9	454.1
Nemyshlainskyi	2229.22	32.1	32.1	292.1
Novobavarskyi	3471.34	75.1	49.4	449.5
Industrialnyi	3339.33	84.9	38.1	346.7
Osnov'yanskyi	4532.45	223.35	15.6	142.0
Total	30607.03	4077.8	449.0	4085.9

It was found that the fallen leaves of the tree hazel contain fiber from 26.1 to 26.8 %, easily fermentable carbohydrates from 13.5 to 14.2 %, starch from 6.2 to 6.8 %, proteins from 17.8 to 18.6 % and lipoids from 8.3 to 8.8 % of the absolutely dry weight of the leaves (figure 1).

At the experimental sites of the Department of Ecology and Life Safety of the Uman National University of Life Sciences, the effectiveness of the use of plant waste to form the initial substrate for vermicomposts was investigated [19].

Based on the results obtained, we propose to develop an environmentally friendly technology for the utilization of urban tree litter, taking into account the peculiarities of the structure of the tree stands of the green zone of Kharkiv. The dominant species in it are sharp-leaved maple (Ácer platanoídes), common chestnut (Aesculus hippocastanum), broad-leaved linden (Tilia platyphyllos) and others. The positive effect of vermicomposting is still expected in relation to

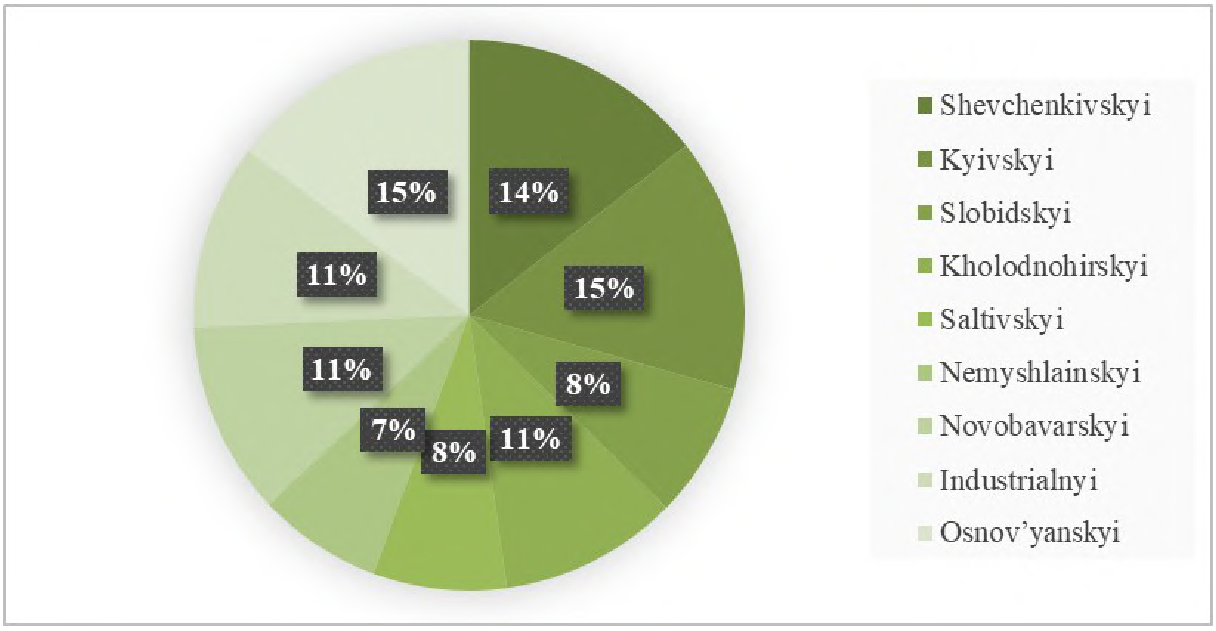

Figure 2. Area of administrative districts of the Kharkiv city, %.

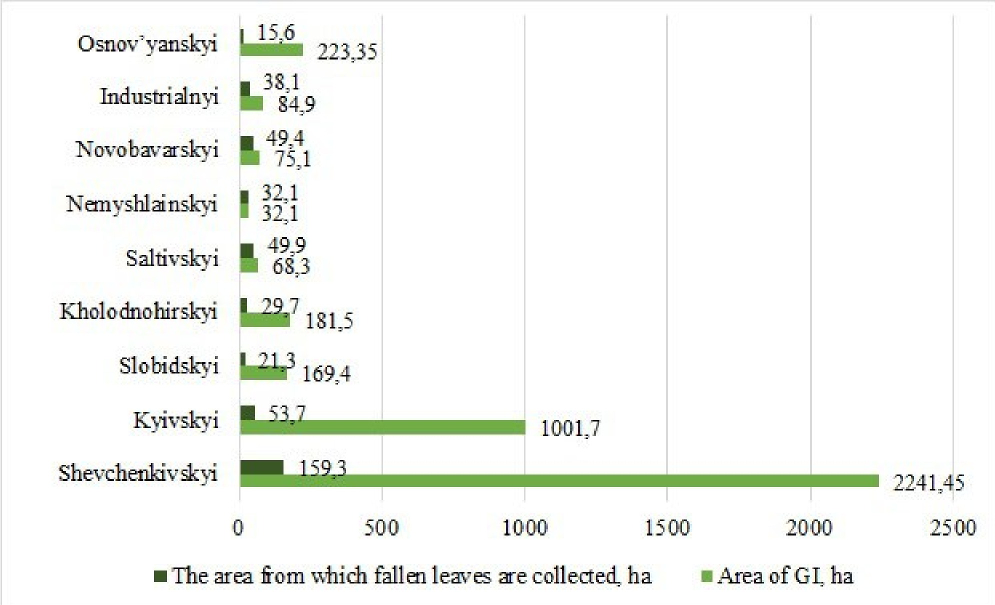

Figure 3. Area of Green Infrustructure in administrative districts of the Kharkiv city and the area from which fallen leaves are collected, ha.

the control of such a pest as chestnut moth, which has become critically widespread in urban plantations.

To estimate the amount of plant waste that can be processed into vermicompost, the following calculations and their analysis were made (table 1).

Kharkiv is a city with a total area of 30607.03 ha, consisting of 9 administrative districts. The largest areas are Kyivskyi (15 %), Osnov'yanskyi (15 %) and Shevchenkivskyi (14 %) (figure 2).

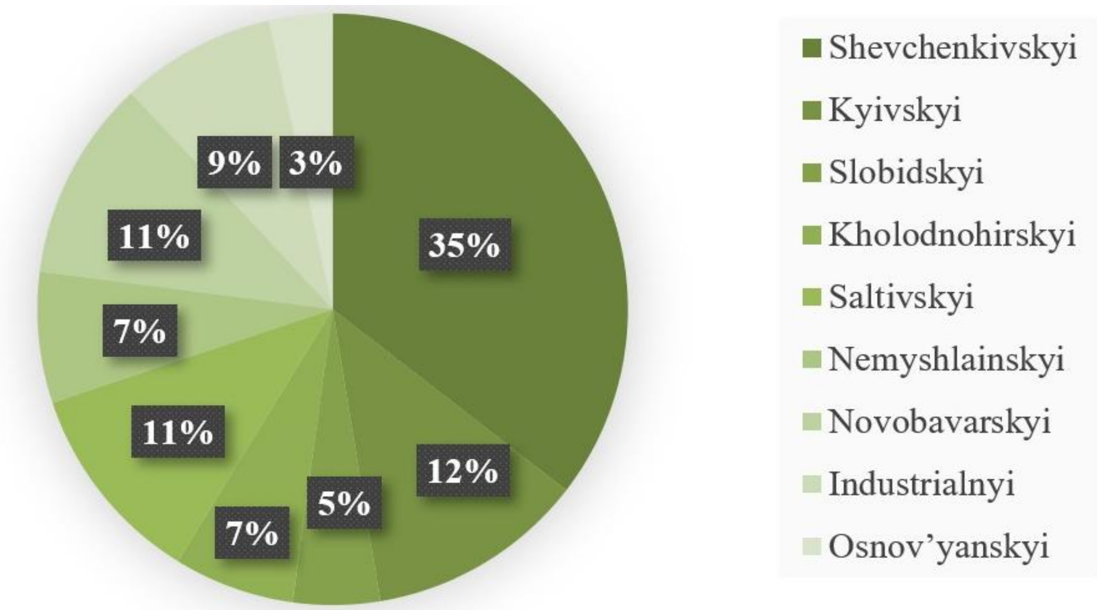

Figure 4. Mass of fallen leaves in administrative districts of the Kharkiv city, %.

Table 2. SWOT analysis of municipal program in-situ utilization of plant waste.

Strengths	**Opportunities**
• Development of environmental principles for the development of green infrastructure of the city on the principles of circular economy • Composting potentially reduces waste management costs, as it avoids waste disposal fees, extends the life of waste and reduces transportation costs. • Nutritious compost substrate compared to soil has a higher (2-3 times or more) content of organic matter, macro- and microelements, mineral and organic colloids. • Its application allows to improve the agronomic properties of the topsoil for 5-6 years, optimizes agrophysical and agrochemical parameters of the soil, improves the use of nutrients by plants, optimizes water consumption. Nutrients are in organic form, so they are reliably preserved from leaching.	• Formation of a culture of nature management among owners of private estates who use their land plots for gardening and horticulture. • Development of in-situ utilization technology, i.e. in-situ utilization of plant organic waste without the need to transport it. • Vermicomposting biohumus has the following valuable properties: high moisture capacity, moisture resistance, hydrophilicity, mechanical strength, does not contain weed seeds. It is able to retain up to 70% of water and is 15-20 times more effective than organic fertilizers. • When applying vermicompost, which is characterized by high buffering capacity, an excessive concentration of salts is not formed in the soil solution, which can be traced in the case of high doses of mineral fertilizers. • For large volumes of plant waste of the city it is advisable to replace vermiculture with a special preparation – organic destructor.
Weaknesses	**Threats**
• There is a need to develop several models that will differ in approaches to waste collection, composting technologies, depending on the characteristics of the city • Generation of large volumes of vegetable waste and lack of infrastructure for their processing. • The dominant way of handling household waste in Ukraine disposal at landfills and dumps. • Lack of environmental education work with the population and the formation of basic environmental knowledge.	• Vermicomposting uses worms for the disposal of plant residues, which do not have any protective organs, so they can be attacked by any animals: rats, mice, snakes, frogs, birds. Necessary to have additional equipment to avoid this. • The processes take place only in warm humid conditions and therefore additional humidification and heating or warm season is required. In winter, it is desirable to keep the worms in a closed warm room at a temperature of up to +10 °C, because at a temperature of +7 °C they go into a state of anabiosis. • The method is difficult to implement for large volumes of waste.

Each district has elements of green infrastructure: parks, forest parks, meadow parks, squares, boulevards, alleys, gardens, forests, etc.

The largest area of organized green infrastructure elements is in Shevchenkivskyi (2241.45 ha) and Kyivskyi (1001.7 ha) districts (figure 3). However, it includes a Forest park, a Hidropark and a Meadow park, which are not the objects of our calculations, since they, as well as forests, nature reserves and some other elements of green infrastructure do not practice the collection of fallen leaves. Therefore, only the part of the green infrastructure where leaf collection is organized in autumn was taken to calculate the amount of plant waste.

The districts with the largest area where leaves are collected include Shevchenkivskyi, Kyivskyi, Saltivskyi and Novobavarskyi (figure 3). Of course, in each of the districts there are intra-quarter plantings and adjacent vegetation, but it is not taken into account in this calculation.

Proceeding from the fact that medieval plantations of broad-leaved species in autumn produce about 9.1 t/ha of fallen leaves, we made the corresponding calculations and obtained the results (table 1), which show the potential of plant residues that can become biohumus and be used for fertilizing urban soils. Comparison of the districts by the volume of plant waste generation showed that almost a third of all residues are produced by Shevchenkivskyi district (35 %), as it is on its territory that the Taras Shevchenko Garden, the Central Recreation Park named after M. Gorky, Sarzhyn Yar, the Botanical Garden and other green infrastructure facilities where fallen leaves are collected are located (figure 4). Kyivskyi, Saltivskyi and Novobavarskyi rayons (11-12 %), with significant differences in the total area and greenery area, have the same percentage of the territory that is maintained and requires organized leaf disposal.

Complex processing of a particular type of plant raw materials is due to the peculiarity of their technological properties and biochemical composition. According to the experience of biotechnology specialists, it is known that organic matter to be vermicultured should contain easily digestible carbohydrates and fiber in an amount of at least 20-25 % [19].

Skip et al. [20] has shown that fallen leaves of broad-leaved linden, sharp-leaved maple, common bitter chestnut trees contain a significant amount of biopolymers, in particular carbohydrates (fiber from 16.3 to 24.6 %, easily fermentable carbohydrates from 6.9 to 12.4 %, starch from 2.5 to 5.8 % of absolutely dry weight of leaves) and other biologically active substances that can serve as a nutrient medium for vermiculture.

Thus, we conclude that the composition of the phytomass of green areas of the city. Kharkiv fully meets the requirements of composting. The use of plant waste processing products as fertilizers using vermiculture significantly reduces the cost of soil enrichment with nutrients, increases the possibility of obtaining environmentally safe products. And what is very important – conditions are created for the utilization (with great benefit) of significant volumes of organic waste.

5. Conclusions

To summarize the collected information, we use the SWOT analysis method, identifying the strengths and weaknesses of the creation of a municipal program for the collection and utilization of plant waste in-sity, opportunities and threats to its implementation (table 2).

The study allowed to draw a number of conclusions that will contribute to improving the quality of ecosystem management of organic residues utilization in urban landscapes. Several environmentally-oriented methods of processing fallen leaves directly on the territory of formation on the principle of in-sity and further use of the resulting product – vermicompost.

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Prospects of the recycling of metallurgical waste

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Prospects of the recycling of metallurgical waste

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Abstract. The article focuses on the peculiarities of waste management of the mining and metallurgical complex. As a result of growing environmental awareness, iron and steel slag is highly valued as a recycled material that can reduce environmental impact due to its resource conservation and energy conservation. The key factors contributing to increasing the attractiveness of investments in the processing of metallurgical waste are: 1. limitation of supplies of primary metal in case of expected growth of demand in the conditions of energy transition; 2. carbon emissions: steel and aluminum together account for almost 10 percent of global emissions, in turn secondary aluminum production creates 5-25 times less carbon emissions; 3. geopolitical instability and dependence on imports from China increase the need to increase the security of supply of primary metals. One of the promising directions of reuse of metals is the production of building materials. Slag is an improved and more ecological alternative to traditional building materials. It can be used in various applications such as filler for concrete and asphalt mixtures, railway ballast, cement, etc. It has been established that the use of slag cement not only provides high-quality concrete, but also prevents global warming, contributes to the conservation of natural resources and minimizes pollution in landfills.

1. Introduction

Metal waste constitutes a significant part of industrial and consumer waste worldwide. Proper handling of them is not only important for reducing the impact on the environment, but also for more rational use and recovery of very valuable resources. Solving the problem of waste disposal has been a priority issue for many years from the point of view of restoring and preserving the state of the environment. The issue of the possibility of circulation of products produced by industrial enterprises is raised immediately before the determination of measures to improve the state of atmospheric air, water bodies, and protect the diversity of flora and fauna. Currently, in terms of industries, the attention of the world community is directed to the waste of the mining and metallurgical complex, in particular to the metallurgical industry, the waste of which is sent to artificially created landfills to a greater extent. Many works are devoted to the study of methods of handling metallurgical residues [1–4].

In Ukraine, metallurgy has been a fundamental branch of the national economy for many decades. Metallurgical plants and steel plants have been the largest tax payers to the budgets of all levels for many years and constantly create new jobs. Ukraine's provision of large amounts of natural resources for many years made it possible not to consider waste as a production material. This has led to the fact that the reuse of metallurgical slag as industrial waste from metal smelting processes is only 40-50 percent, on the other hand, in European countries, up to 90 percent of industrial slag from the total annual volume of formation is processed as components of mixtures for construction, asphalting of roads etc. (in Ukraine, only approximately 20 percent of slag waste is used in mixtures for road construction).

Slags, as industrial waste, according to standard approaches, need to be transported to designated waste storage sites, which causes additional extremely high transport costs, fuel costs, and for giant enterprises – costs for the construction of transport routes.

Currently, due to the military actions on the territory of Ukraine, there is also the problem of disruption of many logistics supply chains, which has a negative impact on the supply of construction material, in particular, stone and other raw materials for the production of concrete mixtures. Therefore, the search for and substantiation of ways to use industrial slag at metallurgical enterprises of Ukraine in order to increase the economic effect for the enterprise itself and for the general ecological effect as a whole is gaining relevance.

2. Results

In terms of environmental security, global organizations and leaders are raising the issue of finding new ways of processing waste. This problem is especially acute in the countries of Europe and the East, because due to the lack of natural resources and the relatively small size of the countries, which does not make it possible to find additional places for landfills and landfills, they are constantly in search of ways to process materials.

During the last decade, the global production of crude steel shows quite high indicators with a mostly positive trend, which, accordingly, causes the aggravation of the problem of handling waste from metallurgical production (figure 1).

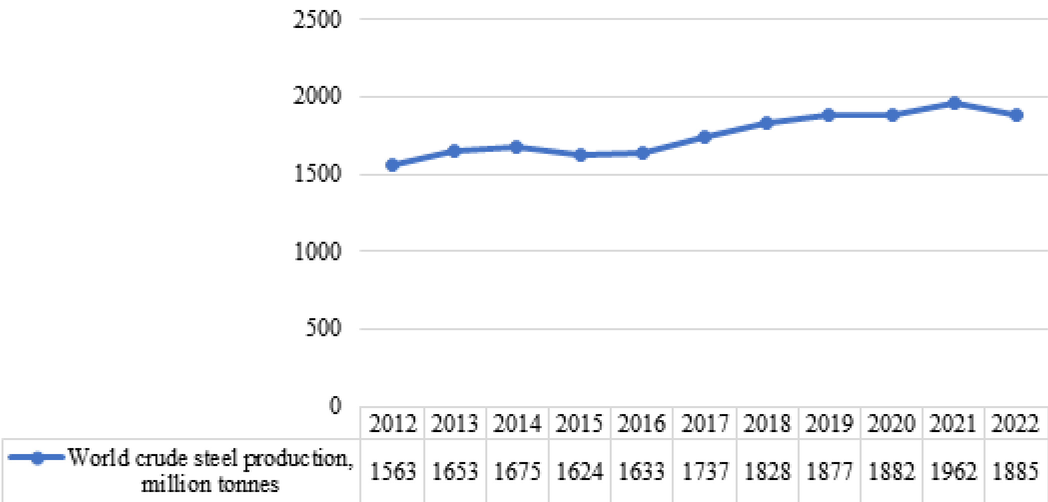

Figure 1. Dynamics of world production of crude steel, million tons (based on the data of World Steel Association [5]).

For a long time, China has remained the key exporter on the world steel market, and the main importer is the United States of America (table 1).

Among the production of basic materials used today, steel production has one of the lowest levels of carbon dioxide emissions per ton of material. However, due to the scale of steel use, the industry is exploring a number of decarbonisation pathways. At the same time, the adoption of

Table 1. Key exporters and importers of steel in the world market [5].

Indirect exports			Indirect imports		
Rank	**Country**	**Mt**	**Rank**	**Country**	**Mt**
1	China	95.8	1	United States	49.0
2	Germany*	32.9	2	Germany*	25.7
3	Japan	21.7	3	France*	13.8
4	United States	20.9	4	United Kingdom	11.9
5	South Korea	17.9	5	Canada	11.6
6	Mexico	17.2	6	China	9.4
7	Italy*	13.3	7	Belgium-Luxembourg*	8.8
8	Poland*	9.9	8	Russia	8.8
9	Spain*	9.5	9	Spain*	8.5
10	Turkey	8.6	10	Italy*	8.5

cyclical principles is an integral part of industrial and social transformation and is an important contribution to achieving the goals of the Paris Agreement.

As a permanent material that can be recycled again and again without losing its properties, steel is a fundamental material for the circular economy. As a result of growing environmental awareness, iron and steel slag is highly valued as a recycled material that can reduce environmental impact due to its resource conservation and energy conservation.

Analysts of the Worldsteel Association in their report Net Zero Steel Pathway Methodology Project list the types of steel production waste and the most diverse ways of their application, including not only road construction, but also the use of carbon and the restoration of biodiversity in water bodies (figure 2) [1].

At the same time, it is noted that waste that has already been used in other sectors is recognized as an effective means of reducing greenhouse gas emissions. In order to achieve the target indicators of sustainable development and reduce the burden on the environment, it is advisable to use metallurgical slag in industrial, road construction and repair, in the production of crushed stone, slag-steel products, use in agriculture as a soil deoxidizer, and the creation of artificial islands like the Japanese ones.

Slag is an improved and more ecological alternative to traditional building materials. It can be used in various applications such as filler for concrete and asphalt mixtures, railway ballast, cement, etc. (figure 3). Historic Roman roads in the county of Sussex in England were built using discarded furnace slag. Since the early 19th century, the United States has used slag in pavement construction as a base and in asphalt mixes, railroads, and cement [6].

The reduction of electricity consumption for the production of cement, lime and metal is also important. Thus, with a comprehensive approach to the processing of solid waste of metallurgical enterprises, it will be possible to significantly reduce the anthropogenic burden on the environment, save scarce building materials and fuel and energy resources for their production.

As governments around the world favor low-carbon concrete in new construction projects, the search for suitable replacements for cement in the concrete mix is at the forefront of new developments in infrastructure technology. Although cement only makes up about 10 percent of the weight of the concrete mix, its production is responsible for 90 percent of the emissions associated with concrete production. The growing demand for low-carbon concrete, combined with the need to meet the growing demand for new infrastructure amid global reconstruction following the COVID-19 pandemic, has made reduced-cement concrete a particularly desirable option [2, 7].

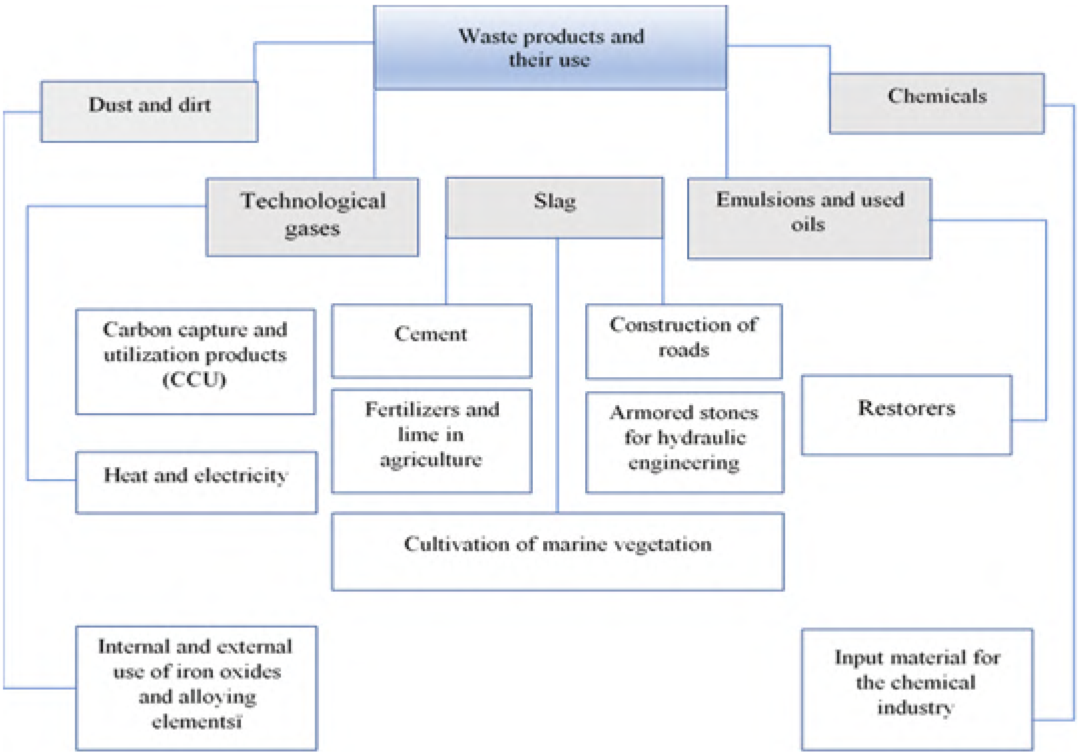

Figure 2. Waste products of metallurgical production (based on the data of World Steel Association [5]).

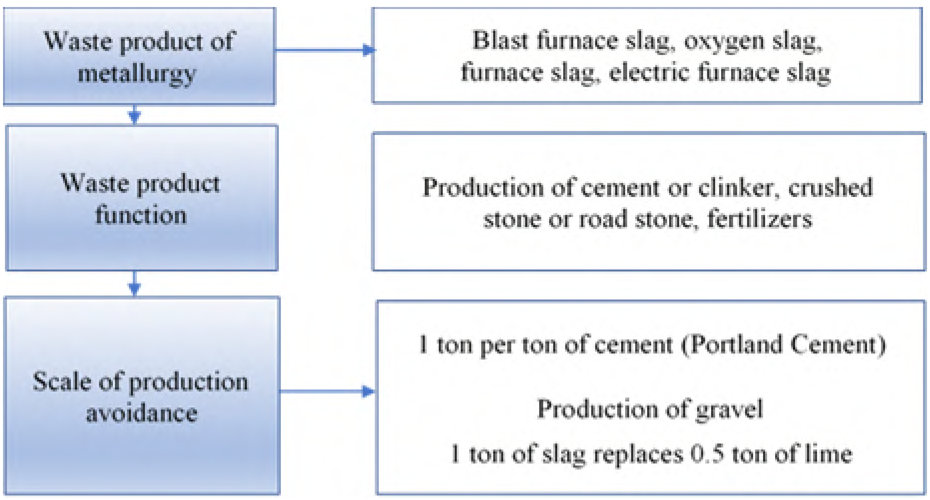

Figure 3. Application of slag waste products of metallurgy (based on the data of World Steel Association [5]).

Slag cement, also known as ground granulated blast furnace slag (GGBFS), is a cement that enhances the strength and durability benefits of traditional concrete while reducing waste, energy consumption and greenhouse gas (GHG) emissions. It is used in construction in combination with traditional Portland cement, as part of a cement mixture or as a separate cement [7, 8].

One of the most important aspects of slag cement is its ability to reduce emissions into the environment, as its production requires less clinker consumption, resulting in lower greenhouse gas and carbon dioxide emissions. Slag cement also reduces the burden on landfills and reduces emissions from the steel industry compared to the traditional process. In addition, the production of slag cement requires 50 percent less energy. Thus, the use of slag cement not only provides high-quality concrete, but also prevents global warming, preserves natural resources, and minimizes landfill pollution [8–10].

3. Conclusions

Leading European countries, in the face of resource scarcity and climate change, are constantly working on finding ways to use waste for re-processing. The countries of the European Union pay considerable attention to the issue of metallurgical waste processing in order to reduce dependence on the shortage of primary raw materials and minimize the impact on the environment. Among the European leaders in the processing of metallurgical waste, Germany, Sweden, the Netherlands and Belgium should be singled out.

- Germany recycling systems are among the most efficient in Europe. Germany has created an effective waste management system that ensures the collection and processing of various materials, including metals.
- Sweden has introduced an innovative system of incentives for the collection and recycling of metal waste, as well as an active company for working with the community.
- The Netherlands shows the best results on the continent regarding the processing of metallurgical waste, and is a leader in the implementation of modern waste management systems.
- Belgium has the most serious and strict metal waste management policy in Europe. Today, we can note the successful use of industrial waste in industrial and road construction, chemical and energy industries, as well as in the agricultural and environmental spheres.

To a large extent, environmental and economic goals can be achieved by finding the use of metallurgical production waste – slag. The use of metallurgical slag as a full or partial substitute for a binding substance (crushed stone) creates a positive economic effect for the enterprise, by reducing waste transportation costs, saving on building materials for the construction and repair of commercial buildings and individual workshops, obtaining profit from the sale of concrete mixture and building materials from it, and the overall ecological effect, making it possible to reduce the burden on the environment by reducing the volume of emissions at artificially created landfills and reducing emissions into the atmosphere during waste transportation.

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Radioecological monitoring as a key factor in food quality management

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Radioecological monitoring as a key factor in food quality management

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Abstract. The effective functioning of radioecological monitoring of food is a crucial task for all countries worldwide as it directly impacts public health. This article confidently describes the migration of radiocesium (Cs) in the environment and its pathways into the human body. The article analyses the data of radionuclide content in food products across France, Spain, Great Britain, Germany, China, and Ukraine. This text confidently compares the regulatory frameworks for food quality management and radioecological monitoring in the mentioned countries. It also provides clear and decisive recommendations for visualising the obtained information on a public portal for scientific research, public awareness, and general use.

1. Introduction

Increased use of nuclear power plants (NPPs), nuclear waste disposal, and radiation technologies in various sectors of the economy inevitably leads to the release of artificial radionuclides into the environment. After nuclear weapons testing and technogenic accidents, more and more citizens around the world began to worry about the quality of food (content of heavy metals, radionuclides, etc.).

Radionuclides that are dangerous to humans, including isotopes of uranium, plutonium, iodine-131, cesium-134, cesium-137, and strontium-90, were dispersed globally through atmospheric circulation and ocean currents following the Chornobyl NPP (ChNPP) and Fukushima accidents.

As these radionuclides share some chemical properties with nutrients, plants and animals absorb them along with necessary nutrients for growth. Several factors influence the radioactivity level of radionuclides in food, such as the radioactivity content of the source environments (soil, water); the availability of nutrients and other substances contained in soil and water; and other environmental conditions affecting animals and plants.

As shown in figure 1, artificial radionuclides migrate through the food chain. Radioactive cesium (Cs) is washed out through atmospheric precipitation and enters the soil, substituted potassium in plants. This process is particularly significant for potassium-rich crops, which can result in radiocesium entering the human body through trophic chains.

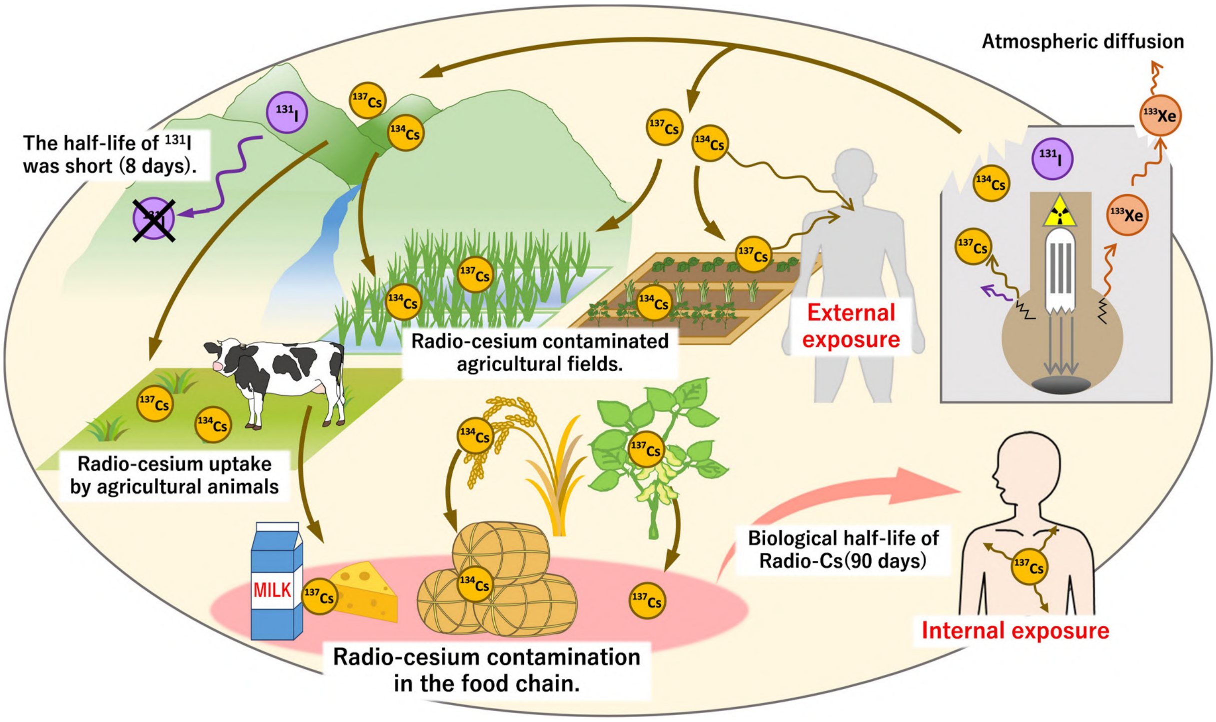

Figure 1. Migration of radiocesium (Cs) in the environment [1].

One of the ways of radionuclides incorporation into biological and food chains may be ingesting of soil particles containing radionuclides during grazing by animals with food. The gastrointestinal tract, kidneys, and mammary glands in lactating animals are the main channels for excreting radionuclides from the mammalian body. Part of the fission products that entered the body of lactating animals excreted with milk.

After cesium-137 and strontium-90 enter the human body, they replace potassium (in muscle tissue) and calcium (in cysts), leading to disease-causing mutations and cancers.

Therefore, to eliminate public doubts and ensure food safety, it is necessary to conduct and implement high-quality radioecological monitoring of natural and artificial isotopes in food to the extent possible.

2. Related work

The study has resulted from an in-depth analysis of wide range of legislation, scientific publications, and information sources. The result of the analysis showed that the problem we outlined is considered and described in the following areas:

- development and use of equipment for radioecological monitoring [2–4];
- use of monitoring data to solve problems of management of radiation-contaminated areas [5–7];
- study of radionuclide migration through trophic chains [8–11];
- peculiarities of functioning and regulatory and legal support of radioecological monitoring of food products [12–14].

The article [15] examines the peculiarities of food control in the member states of the European Union. These states are obliged to carry out radioecological monitoring of food products and environmental components from the moment of signing the Euratom Treaty. However, we would like to note that there is no newer information on radioecological monitoring (at the time of writing this article) since there is no published information on radio-ecological monitoring in the information access (official websites of the organizations conducting this monitoring, as well as the International Atomic Energy Agency (IAEA) monitoring, methods and methods of determining the level of radioactivity in various components of the environment, according to which certain indicators were determined. Therefore, the authors refer to the generally accepted methods of determining the radioactivity of radionuclides in food products.

Máté, Sobiech-Matura and Altzitzoglou [16] note that to carry out monitoring, it is necessary that the procedures for responding to emergency situations with a radiation factor be implemented and well known to all participants in the process, both from a legal and from a regulatory point of view. For this purpose, a database of environmental radioactivity monitoring was created in the European Union in 1988, with the help of which you can view information that is available to the public [17,18]. However, we would like to note that this database contains information until 2020. That is, generalized information on radioecological monitoring of food products of all EU countries for 2024 is not available.

Monitoring data is crucial in detecting any increase in radiation levels in food products and the environment. This information is used to take appropriate response measures. In the absence of measurement data, scientists rely on mathematical models to predict radiation exposure, which requires monitoring data for identification and verification. You can find more information on this at [19].

Radioecological monitoring of food products is crucial, as demonstrated in the work mentioned in [20]. In response to the Fukushima Daiichi accident in 2011, Japanese authorities established temporary regulatory values for radionuclides in food. A year later, current regulatory values were set and regularly monitored by checking radionuclides in food. Any food item that exceeded the standard limits was not distributed due to Japan's rigorous food management system.

After the accident at the Chornobyl Nuclear Power Plant in 1986, a similar situation arose. Radionuclides spread in the territories of Ukraine, leading to the establishment of temporary regulatory values for food products. It was only in 1997 that radiation safety standards were approved in Ukraine, specifying the permissible levels of radiation.

Thus, effective functioning of radioecological monitoring of food is a crucial task for every country worldwide as it directly impacts public health.

Objective: to analyse the data and compare the regulatory framework for food quality management within the framework of radioecological monitoring.

3. Results of the study

Radioecological monitoring is the collection pf primary information (measurement of the dose rate absorbed in the air, determination of the content of radionuclides in environmental objects, food, drinking water, etc.) for the purpose of its further use for radiation-hygienic and domestic monitoring. The control of food for radionuclide content is a crucial component of radioecological monitoring [2].

Internal exposure resulting from the ingestion of radioactive substances present in crops and livestock products in the primary cause of radiation dose in individuals living in areas contaminated with radionuclides.

The following section will analyse data on the radionuclide content in food, allowing us to identify the specificities of radioecological monitoring in different countries worldwide.

3.1. France

Monitoring of radioactivity in food in France at the national level is carried out by the Direction générale de l'alimentation (DGAL) in cooperation with the Institut de radioprotection et de sûreté nucléaire (IRSN) [21]. This includes:

- monitoring of foods exposed to potential sources of radioactive contamination (areas close to the nuclear base);
- light departmental monitoring: characterisation of the radiological quality of food (in particular, mil) outside the direct influence of the most important nuclear facilities;
- monitoring in areas affected by radioactive residues (zones de remanence);
- coastal monitoring.

The most important radionuclides tested are ^{134}Cs and ^{137}Cs. The IRSN carries out additional analyses on the samples submitted to check for several natural and artificial radioactive elements. To ensure that samples are representative for certain types of analysis (especially considering seasonal random factors), milk sampling may distribute over the year. In these cases, a sample is taken from the following the same producer for each quarterly or half-yearly sample. In addition to collecting milk samples from farms located near nuclear facilities, samples from cooperatives or dairies allow representative reference values to be obtained for the total production of cow's, sheep's, and goat's milk in the region and for health monitoring at national level. This monitoring also allows the maintenance of a network of competent laboratories [21]. This network is vital in the event of a crisis. The sampling frequency (in most cases annual) can increase in case of a radiological event. At the Orano La Hague site, there are three sampling points in Digulleville where the Ministry of Agriculture takes a milk sample every quarter and sends it to the IRSN. There is analysis for free tritium, ^{129}I, ^{14}C, ^{90}Sr and gamma emitters. One meat sampling point is selected annually to analyse bound tritium, ^{14}C, ^{90}Sr and gamma. As part of the coastal monitoring, three sampling points located in the municipalities of Barfleur, Goury and Saint-Georges-de-la-Riviere, where fish are sampled annually for bound tritium,^{14}C, ^{90}Sr, plutonium isotopes, ^{241}Am and gamma emitters.

3.2. Spain

The Spanish Nuclear Safety Council (CSN) manages the National Radiological Surveillance Network, consisting of automatic and sampling stations. This network provides information on the levels of radioactivity in air, water, soil and basic foodstuffs [22].

Let us consider how the radioecological monitoring of food is carried out in the city of Palomares. The main economic activity of this town is intensive agriculture, namely animal products such as milk, honey, and fish. Intensive radioecological monitoring has been carried out in this region for about 50 years due to the release of plutonium and other radioactive materials following the crash of North American military aircraft, one of which was carrying thermonuclear bobs [9].

Cultivated vegetables are collecting at 16 stations in different farms. Intensive agriculture is carried out both in open ground and in greenhouses. The main products harvested are lettuce, peppers, cucumbers, peas, lima beans, watermelons, tomatoes, zucchini, green beats, broccoli, oranges, olives, etc. The type of vegetables accepted at each station may vary in different seasons, depending on the choice of the owner who grows them. Edible animal products such as honey, goat's milk and fish are collecting near Palomares. All these foods are analysing for $^{239+240}$Pu and ^{241}Am at the RERA laboratories in Madrid [22, 23].

3.3. The United Kingdom

In England and Wales, the Food Standards Agency and the Environment Agency monitor food and non-food (including seawater, sediments, and dose rates). The Scottish Environment

Protection Agency and the Northen Ireland Environment Agency monitor food and non-food products in Scotland and Northern Ireland respectively. Food monitoring includes the collection and analysis of cow's milk. The Food Standards Agency and the Scottish Environment Protection Agency also monitor milk and table food remotely collected from nuclear-licensed sites in the UK [24].

The Northern Ireland Environment Agency monitors the long-range impact of liquid discharges from the UK's largest nuclear complex, Sellafield, into the Irish Sea. It is sampling fish, shellfish and indicator materials from several locations along the coastline (figure 2).

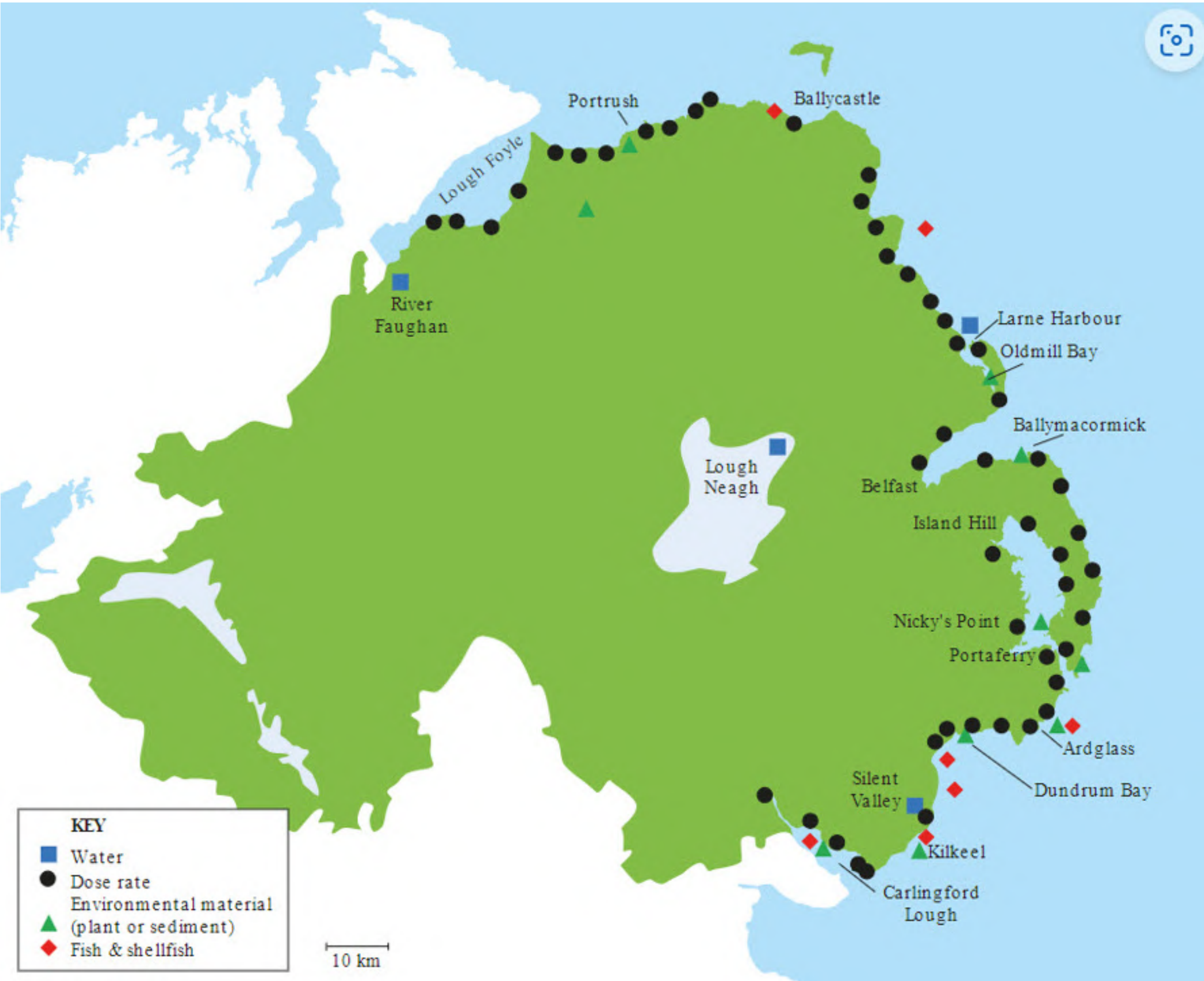

Figure 2. Monitoring sampling locations in Northern Ireland [24].

In 2022, the main effect of Sellafield releases was observed in technetium-99 concentrations in shellfish and seaweed samples. Concentrations of cesium-137 were low and generally similar to those observed in 2021. Low levels of transuranic radionuclides have also been detected in 2022. Table 1 shows the concentrations of radionuclides activities in seafood from Northen Ireland [25].

In 2022, a programme was implemented to sample at UK dairies for radionuclides. This programme provides helpful information that can be used to compare data from farms located near nuclear-licensed facilities and other establishments that may increase values above background concentrations of radionuclide activity [24].

The results of milk monitoring in 2022 were similar to those of previous years, Average carbon-14 concentrations in England, Northern Ireland, Wales and Scotland were close to the expected

Table 1. Concentration of radionuclides in seafood in Northern Ireland.

Material	Location	Mean radioactivity concentration, Bq/kg					
		^{14}C	^{60}Co	^{99}Tc	^{125}Sb	^{134}Cs	^{137}Cs
Cod	Kilkeel	29	<0.06	–	<0.12	<0.06	0.36
Plaice	Kilkeel	–	<0.04	–	<0.10	<0.04	0.22
Herring	Ardglass	–	<0.09	–	<0.24	<0.12	0.26
Crabs	Kilkeel	–	<0.06	–	<0.15	<0.07	<0.09
Lobsters	Kilkeel	–	<0.06	6.5	<0.13	<0.08	<0.10
Mussels	Carlingford Lough	–	<0.10	2.1	<0.20	<0.11	<0.25

background concentration in milk. The maximum carbon-14 concentrations in milk for England (Dorset and Kent), Northern Ireland (Co. Tyrone), Wales (Clwyd) and Scotland (Dumfriesshire and Nairnshire) were 22, 25, 43 and less than 16 Bq/L, respectively. As in previous years, tritium concentrations were below the limit at all remote sites. Strontium-90 concentrations were below (or slightly above) the values in 2022, with the UK average concentration being less than 0.033 Bq/L in 2022 (0.037 Bq/L in 2021). In the past, the highest concentrations of radiocesium in milk were in the regions that received the highest amount of radioactive fallout from Chornobyl. However, now the concentrations are very low, and it is impossible to distinguish this trend [25, 26].

The programme to monitor natural and artificial radionuclides in crops (in England, Wales, and the Channel Islands) as a check on general food contamination (away from nuclear facilities) was discontinued in 2014 [25].

3.4. Germany

Radioecological monitoring of food in Germany carried out by the Bundesamt für Strahlenschutz. In the past, artificial radionuclides from the atmosphere have been deposited on plant and animal food in Germany following the Chornobyl accident and atmospheric nuclear weapons testing. Southern Germany was particularly affected by the Chornobyl accident. Today, food produced in Germany has cesium-137 levels of a few becquerels per kilogram fresh weight or less. However, some types of edible wild mushrooms and game such as wild boar, may have significantly higher levels of contamination [27].

As part of the Integrated Measuring and Information System for the Surveillance of Environmental Radioactivity, samples of agricultural products and drinking water produced in Germany are regularly [28].

In modern laboratories in Berlin, the raw milk from farms in the suburbs of Berlin was analysed for ^{90}Sr. Milk samples were subjected to gamma spectrometric analysis.

Plants, food, and feed are analysed based on the National Metrological Institute's nuclide library, which is constantly updated with the latest available information. Data on the following nuclides are provided regularly: ^{40}K, ^{60}Co, ^{103}Ru, ^{131}I, ^{132}Te, ^{134}Cs, ^{137}Cs, ^{144}Ce. Reporting obligations for monitoring programmes under the REI Guidelines are limited ^{40}K, ^{60}Co, ^{134}Cs and ^{137}Cs. Any additional nuclides detected during analyses (e.g. ^{7}Be) are also reported [28].

Other foodstuff (meat of cows, calves, pigs and poultry) is also subject to gamma spectrometric analysis as foodstuffs of animal origin. About 20 measurements are carried out each year. Samples (approximately 1.5 to 2.5 kg each) are purchased from regional farms or slaughterhouses [28].

Regular official monitoring of imported foodstuff does not include measures to detect potential radioactive contamination. However, imported goods may be inspected for the Fukushima and Chornobyl accidents. Samples are taken at the veterinary border inspection post at Berlin-Tegel airport. Samples are tested at the radiation monitoring station of the Berlin-Brandenburg State Laboratory in [27, 28].

3.5. China

National Nuclear Safety Administration (NNSA) is improving the management of the national environmental radiation monitoring network. The NNSA is providing recommendations to environmental protection authorities in all provinces, autonomous regions, and municipalities. The NNSA is also strengthening radioecological monitoring of the marine environmental in connection with the release of treated wastewater from the Fukushima NPP in 2023. A programme has been confidently developed to create comprehensive plans or monitoring radioactivity in the marine environment. Ongoing and decisive work is being done to ensure the highest quality of radiation monitoring [29].

Figure 3 displays the activity concentrations of ^{90}Sr (A) and ^{137}Cs (B) in various food samples collected around different NPPs in China from 2012 to 2019. The presented figure demonstrates that the radionuclides concentrations found in rice, salsa, muller, and crucian carp are well below the regulatory limit for general-purpose food in China. Therefore, we can confidently conclude that during the specified period, the food in the vicinity of the NPP was within the normal range [30].

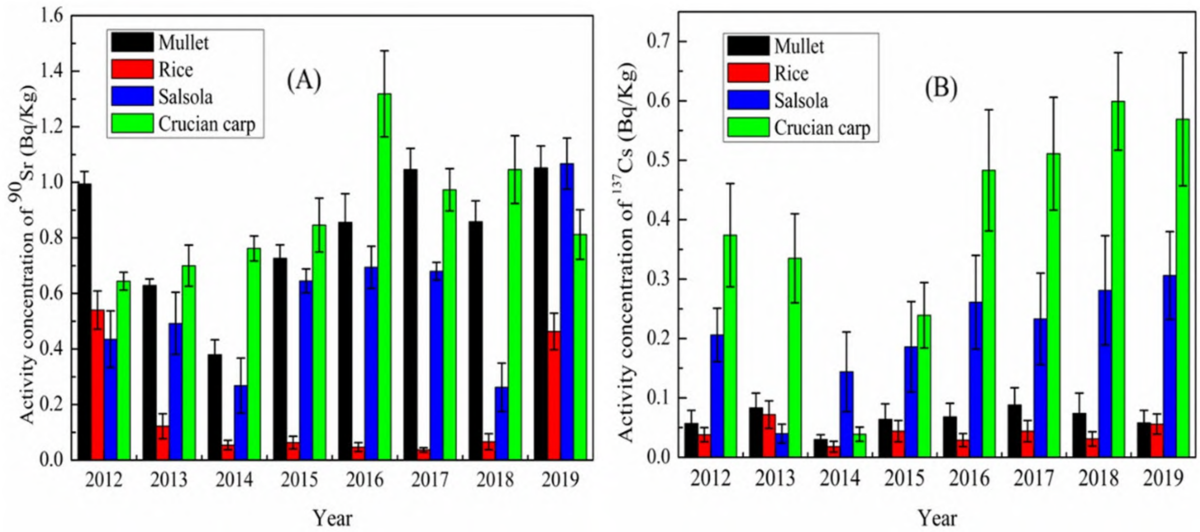

Figure 3. Radionuclide activity concentrations in different food samples [30].

According to [31], hairtail had relatively high concentrations of ^{137}Cs, with the maximum value (0.13 ± 0.01 Bq/kg) observed in 2015. All samples of milk, kelp, and crucian carp had concentrations of ^{137}Cs below the respective minimum detectable activity concentrations. Most samples of rice and salsola also had concentrations below the minimum detectable activity. The measured activity concentrations of ^{90}Sr from 2012-2019 in milk, rice, salsa, kelp, grass carp and crucian carp fall within the ranges of (0.11 ± 0.06) -(0.30 ± 0.04) Bq/l, (0.029 ± 0.009)-(0.16 ± 0.08) Bq/kg, (0.081 ± 0.008)-(0.64 ± 0.06) Bq/kg, (0.067 ± 0. 023)-(1.3 ± 0.4) Bq/kg, (0.18 ± 0.06) -(0.74 ± 0.10) Bq/kg, (0.33 ± 0.08) -(1.10 ± 0.05) Bq/kg, respectively. It was noted that the concentration of ^{90}Sr varied significantly depending on the type of food. Elevated mean ^{90}Sr

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levels were observed in rice, salsola, and crucian carp from the vicinity (Haiyan/Haining) of the Qinshan NPP from 2012 to 2019 when compared to food from Hangzhou. This is a probably due of the impact of radioactive releases from the Quinshan NPP [31].

3.6. Ukraine

The State Service of Ukraine on Food Safety and Consumer Protection carries out radiation monitoring of the level of radioactive contamination of agricultural products and food by the legislation of Ukraine (`https://zakon.rada.gov.ua/laws/show/667-2015-%D0%BF#n9`). All information on the level of activity of radionuclides in food in different regions of Ukraine is available on the website of this institution (`https://dpss.gov.ua/`). The monitoring laboratories of the Ministry of Agrarian Policy and Food of Ukraine also carry out monitoring in place of concentration of radioactive substances in soil and food. The Ukrainian Research Institute of Agricultural Radiology (a structural unit of the NULES of Ukraine) deals with radiation monitoring of agrobiocenoses, including radiation monitoring of products in contaminated areas. For information on ^{137}Cs contamination in food, please visit `http://uiar.org.ua/Ukr/index.htm`.

In paper [32] describes the results of a study of ^{137}Cs and ^{90}Sr radioactivity in vegetable crops grown in the Kyiv region in 2015-2018. The study found that the lowest ^{137}Cs activity was in potatoes, onions, and cucumbers. It was twice as high in zucchini and bell peppers, almost four time higher in carrots and tomatoes, almost eight times higher in beets and radishes, and 11 times higher in beans. The activity of ^{90}Sr in vegetable crops varied significantly across different types of vegetables. Onions had the lowest activity, while tomatoes and cucumbers had twice as much activity. Sweet peppers had four times higher activity, potatoes and cabbage had almost ten times higher activity, and zucchini had twenty times higher activity. Table beets, carrots, radish, and beans had the highest activity, with thirty times higher activity compared to onions.

The study [33] investigated the content of certain pollutants, such as heavy metals and radionuclides, in meat from various types of industrial production animals sold in retail chains in the Kyiv region. The analysis of radionuclide accumulation in the studied meat products confirms that their contamination level was well below the national maximum permissible levels of radionuclides in food products regulated by the state hygiene standards.

4. Discussion

Although radionuclides occur naturally in the environment, their presence can have negative impacts on living organisms. Accidents at nuclear power plants like ChNPP in Ukraine and Fukushima-1 NPP in Japan, as well as nuclear weapons testing, have released artificial radionuclides into the environment, increasing the level of radiation in various parts of the world. Given the continued growth of the nuclear industry and the potential for accidents at nuclear facilities, it is essential to regularly monitor the presence of radionuclides in various settings, including food products, water samples, and the air we breathe. This is a critical task for organizations at all levels to ensure a safe and comfortable life for society.

The IAEA is responsible for regulating the use of nuclear energy and weapons throughout the world. This agency establishes safety and environmental standards related to nuclear activities. All countries that utilize nuclear installations for scientific or civil purposes must provide detailed reports on their operation, including information on the nuclear fuel cycle and environmental pollution control measures.

Various emergencies with a radioactive damage factor inevitably have a certain impact on food and drinking water. To provide the population with high-quality food products, it is necessary to constantly carry out radioecological monitoring of food products and visualize (make public) the relevant information obtained for the public's awareness.

The authors of this study gathered and analysed data from open sources to determine the level of radionuclides in food products in different countries. They compared the content of the two most common artificial radionuclides, strontium-90 and cesium-137, which can be life-threatening as they can replace potassium and calcium in the body. The study also examined how the levels of these radionuclides compare with the national standards of different countries. These radionuclides are formed during the decay of uranium and are present in most parts of the world as pollutants. Table 2 shows the permissible levels of ^{137}Cs and ^{90}Sr radionuclides in different food products in Ukraine, the European Union, China, and South Korea.

Table 2. Radioactivity levels of 137-cesium and 90-strontium in food products in different countries according to their legislation (Bq/l, Bq/kg) [34–37].

№	Material	Ukraine		The European Union		China		South Korea	
		^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
1	Milk and dairy products	100	20	1000	125	330	33	50	10
2	Meat and meat products	200	20	1250	750	290	800	100	1000
3	Fish and fish products	150	35	1250	750	290	800	100	1000
4	Baby food products	40	5	400	75	300	41	50	10
5	Vegetables	40	20	12500	7500	210	77	100	500
6	Potato	60	20	12500	7500	90	33	100	500
7	Grain	50	20	12500	7500	260	96	100	500

From the above limit requirements (norms) for radioactive substances in food in different countries for the sake of human health, each country/region has formulated limit requirements for radioactive elements based on national conditions and food safety perspectives. Given the constant attention to various emergencies with a radioactive damage factor and to reduce the circulation of food with a high content of radionuclides during import, each country ensures strict compliance with the relevant regulations.

Based on table 3, we can conclude that Ukraine has the most stringent regulations on the maximum content of radionuclides in food. After analyzing the IAEA publications, we have compiled table 3 that shows the permissible levels of radionuclides in food products in Ukraine following the accident at the Chornobyl nuclear power plant. It is worth noting that monitoring the migration of radionuclides and their impact on the population has enabled us to determine the maximum level of radionuclide contamination in food products and take appropriate measures. This has helped in reducing the mortality rate among the population and livestock, ensuring a safer life for all.

5. Conclusions

According to the Euratom Treaty and several IAEA treaties, countries that possess nuclear technology must perform radioecological monitoring of the environment and food products.

Table 3. Temporary permissible levels (TPL) of the content of radionuclides in food products (according to IAEA data) (Bq/l, Bq/kg).

№	Material	The date of approval of the TPL after the accident at the ChNPP				
		06.05.1986	30.05.1986	15.12.1987	06.10.1988	22.01.1991
1	Milk and dairy products	3700	370	20	20	20
2	Meat and meat products	-	3700	1850	1850	740
3	Fish and fish products	37000	3700	1850	-	740
4	Baby food products	-	-	370	370	185
5	Vegetables	-	3700	740	740	600
6	Potato	-	3700	740	740	600
7	Grain	-	370	370	370	370

This is necessary to ensure a swift response in case of an emergency that involves radiation damage and to guarantee a secure life for society. All relevant information regarding the level of radioactivity in the environment should be made available for public access by the above-mentioned documents.

This work has compiled and analysed information from open sources around the world concerning the monitoring of radioactivity in food products. This allows for the dissemination of information to the population regarding the levels of radioactivity in their food, as well as the points where raw materials are selected and laboratories that conduct analyses to determine radioactivity.

The comparison of the maximum allowable levels of radionuclides in food products according to the legislation of different countries revealed that Ukraine has the most stringent standards for the maximum content of 137-cesium and 90-strontium.

The authors of a publication suggest that due to the significant delay (usually 3-4 years) in updating data on radioecological monitoring of food products, it would be beneficial to have a single portal where information on the contamination of food products with radionuclides can be published. The European Radiological Data Exchange Platform (EURDEP) could be utilized for atmospheric air radiological monitoring data, making the information readily available for public use, scientific research, and public awareness. This approach would enhance the effectiveness of radioecological monitoring efforts.

Author contributions

The following research results presented in the publication are the joint contribution of individual authors:

- **Andrii V. Iatsyshyn**: idea generation, research relevance substantiation, and preparation of the draft article. Also, analysis of literary sources regarding monitoring of food products, monitoring and regulatory framework in Ukraine, and identification of monitoring subjects.
- **Valeriia O. Kovach**: analysis of literary sources regarding the regulatory framework of the European Union, works related to the monitoring of food products in France, and

maximum permissible levels of 137-cesium and 90-strontium in food products in different countries according to their legislation.

- **Anastasiia M. Lahoiko**: justification of the research relevance, analysis of literary sources regarding food monitoring in Great Britain, availability of various reports on permissible levels of radionuclides concentration in food, impact of ChNPP and Fukushima-1 accidents on the quality of food products, and comparison of the regulatory framework of the studied countries regarding the concentration of radionuclides.
- **Viktor O. Gurieiev**: analysis of literary sources regarding the regulatory framework for the concentration of radionuclides in food products in Asian countries and peculiarities of the functioning of food monitoring in China.
- **Anna A Humeniuk**: analysis of the availability of different reports on permissible levels of radionuclides in food in Germany and Spain.
- **Inna A. Semenets-Orlova**: analysis of literary sources regarding the monitoring of food products and temporary permissible levels of radionuclide content in food products.
- **Roman Shevchuk**: functions and role of food quality management in the aspect of radioecological monitoring.

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Natural phytomelioration of coal mine waste heaps in the context of increased radiation background (on the case of Nadiya mine, Lviv-Volyn coal basin, Ukraine)

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Natural phytomelioration of coal mine waste heaps in the context of increased radiation background (on the case of Nadiya mine, Lviv-Volyn coal basin, Ukraine)

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Abstract. At the United Nations Climate Change Conference (COP26) in Glasgow in autumn 2021, world leaders and participants decided to phase out coal power. Ukraine is committed to shutting down its state-owned coal-fired power plants by 2035. Natural and technical geosystems in coal mining areas have a significant impact on environmental and anthropogenic environmental safety and require comprehensive researchThis scientific article delves into the thorough examination of the impact of augmented radiation levels in the waste piles of the Nadiya mine in the Lviv-Volyn coal basin. The exploitation of the Lviv-Volyn coal basin has led to many negative changes in the flora and fauna, atmosphere, hydrosphere and biosphere, and has significantly affected the life and health of the Ukrainian population. The Nadiya mine waste heaps are located on the outskirts of the town of Sosnivka, Chervonohrad district, Lviv region (Ukraine) on fluvioglacial sands, partially on alluvial sediments of the Western Bug River. The height of the waste heaps is over 42 m and the area is 12 hectares. The spoil heap is bounded by woody vegetation on both sides and agricultural land on the other. The spoil heap is composed of burnt and unburnt rocks with sulfuric acid zones on the burnt pieces. Spontaneous combustion is observed on the spoil heap, in particular at the top, where the radiation background was investigated. The radiation power at the top of the spoil heap was found to be significantly higher than in other areas. The investigations of the radiation background of the Nadiia mine spoil heap showed the equivalent dose rate at the top of the heap, which is 0.42 μSv/h, exceeding the permissible standards of 0.3 μSv/h. It should be noted that the excess radiation background is due to the combustion of rock.

1. Introduction

The coal industryis the basis for sustainable development of the national economy and energy security. Coal mining areas are often plagued with an array of environmental and socio-economic issues, such as land deformations, flooding, salinization, underground and surface water pollution, and depressed zones, all of which pose significant challenges. Coal mines in Ukraine are developed with old and dilapidated coal equipment in challenging mining and geological environments. Chronic underfunding of coal mine environmentalization projects has led to serious changes in the environmental state of the affected areas [1, 2]. The depletion of balance sheet reserves, unprofitability of most mines, difficult geological conditions of mining, and unstable economic situation have led to large-scaleliquidation of mining enterprises. The heightened danger of surface subsidence, flooding of lands, drastic alterations in ground and surface water quality, and impairment of structures and facilities is a direct consequence [3]. Coal mining destroys the landscape and also causes large amounts of wastewater entering mine workings. The treatment of mine water in closed mine reservoirs remains unresolved, and standards governing its discharge into the hydrological network remain to be defined. Mine water contaminated with mineral salts, suspended solids, sulfates and other pollutants causes contamination of aquifers and disruption of their hydrology [4].

The geographical location of the Lviv-Volyn coal basin corresponds to the Lesser Polissya area, whose climate is influenced by Atlantic air masses. Since the Chervonohrad mining district of the Lviv-Volyn coal basin was the first to be developed, its waste heaps contain the largest amount of rock. One of the largest mines in the district is the Nadiya mine, with a waste heap volume of over 2869.4 thousand m^3. The ash content in the rock is over 83.1% and sulfur is 2.4%The density of the rock is over 2.25 kg/m^3. The base area of the waste heap is 120 thousand m^2, the height is 53 m, the angle of rock dumping along the contour is 36°, and the annual rock supply to the heap is more than 9.8 thousand m^3 (according to the Passport of the waste heap No. 1 of the Nadiya mine, as adjusted in September 2021). In general, rock dumping began in August 1962, and rock combustion began in September 1963 and continues in several locations to this day. Intensive rock combustion took place from 1975 to 1979 [5]. Currently, the surface of the waste heap is inhabited by pioneer species, including the moss *Campylopus introflexus*. Within a relatively short period of time, *Campylopus introflexus* has significantly increased the projective cover on the waste heap, additionally, the species contributes to the accumulation of organic carbon and the formation of a humus layer of the substrate. It was noted that a decrease in the chlorophyll *a/b* ratio, and an increase in the content of chlorophylls versus carotenoids under conditions of inhibition of chlorophyll photochemical activity play an important role in protecting the photosynthetic system of C. *introflexus* [6, 7].

Considering the numerous scientific studies of [8–10] related to the assessment of the environmental hazard of coal mine waste heaps, it should be noted that the problem is extremely relevant today. Technogenic and environmental safety of coal mines directly depends on the state of financing and timeliness of environmental protection measures. Identifying and eliminating the root causes of an environmental issue is usually a more cost-effective strategy than the present expenses incurred in battling the aftermath of the same issue. Mining activities lead to a number of phenomena and processes that have a negative environmental and technological impact. These phenomena and their consequences are currently poorly understood, unpredictable and mostly uncontrollable. The potential danger posed by a waste dump to the environment is influenced by various factors, including the chemical and mineral makeup of the rocks, physical and chemical properties of internal and external transformation along with climatic and hydrogeological conditions, sensitivity of degradation processes, and heightened radiation levels [11]. Each waste heap has certain characteristics and a specific negative impact on the environment, flora and fauna, and human health, depending on its location [12]. The degree and scope of the impact caused by a human-made hazard is determined by its geographical placement and the individual who is affected by its adverse effects [13, 14].

Thus, factors such as the age of the dumping and the processes of combustion of waste rock prompted us to investigate the technogenic hazard of the Nadiya mine dump in the Lviv-Volyn coal basin [15].

2. Material and methods

2.1. Edaphic and climatic conditions of the research

Chervonohrad is situated in the northern region of Lviv oblast, at a distance of 80 km from the oblast's center and 70 km from the border with the Republic of Poland. The area of the region is 21 km^2 (Chervonohrad – 17.8 km^2; Sosnivka – 2 km^2; Hirnyk – 1.2 km^2). The study area is characterized by the dominant processing and mining industry. The city of Chervonohrad is located in the Western Ukrainian forest-steppe zone and Lesser Polissia, at the confluence of the Solokia and Rata tributaries into the Western Bug River. Chervonohrad is located in a humid, moderately warm agroclimatic zone with sufficient soil moisture. The climate is temperate continental, characterized by mildness and high humidity. Main natural resources: Zabuzhske and Mezhyrychanske coal deposits. The region has over 2097 hectares in use, including 1779 hectares in Chervonohrad, 198 hectares in Sosnivka, and 120 hectares in Hirnyk. The Nadiya mine is located on the outskirts of Sosnivka on fluvio-glacial sands, partly on alluvial deposits of the Western Bug River, and has been in operation since 1962. The height is over 42 m, the base area is over 12 hectares. The spoil heap is bounded by woody vegetation on both sides and agricultural land on the other [16]. The elevated section comprises embankments, depressions, and overgrown regions. The spoil heap is formed by burnt and unburnt rocks with sulfuric acid zones on the burnt pieces. Linear erosion is present on the side surfaces [17]. In some places, the slopes of the waste heap are quite steep and abrupt and form vertical walls. The southeastern side of the spoil heap and the western part of the spoil heap are covered with mine rock, making the topography of the spoil heap even more complicated [18–20].

2.2. Edaphic and climatic conditions of the research

We chose 7 different sites near the Nadiya mine to analyze the environmental situation and take substrate samples for radiation background analysis. The samples were taken from depths of 0-15 cm and 0-20 cm, as well as from an anthropogenic reservoir which accumulated the waste formed from anthropogenic activities (figure 1).

Seven study areas of the Nadiya mine were selected to study the radiation background of the waste heap, since the combustion process was observed there: 1 – at the foot of the spoil heap in relatively favorable growth conditions; 2 – on the slope, where intensive water-erosion outcrops 1-2 m wide and 0.5-1 m deep are present; 3 – on the terraced slope, with numerous places of water-erosion outcrops (1-1.5 m wide, 0.5-1 m in width, 0.5-1 m in depth), deflation (wind erosion), places of fire, discharge of fuels and lubricants, household waste, as well as increased soil cover density, and as a result, almost complete absence of above-ground grass cover; 4 – at the foot of the spoil heap of the forest area, in some places there are traces of soil washout and exposure of tree root systems (danger of tree fall); 5 – on the top of the waste heap, mostly flat with small hilly areas and minor relief depressions; 6 – control, at a distance of 3 km from the waste heap in the forest area with practically no anthropogenic impact (there are natural forest roads); 7 – from an anthropogenic reservoir, at a distance of 2 km from the western side of the waste heap.

2.3. Research devices

The radiation levels of the waste heaps were measured with the SOEKS environmental tester (shown in figure 2) in compliance with the guidelines of Ukraine's Radiation Safety Standards (NRBU-93) [21]. Modeling of radiation background is carried out using computer program Surfer. The intensity of illumination was determined using a digital luxmeter with a remote sensor (model LX1010BS, measuring range 1-100000 Lx), measurement accuracy ± 4% operating temperature of the environment -10°C...+50°C. Humidity and air temperature were determined using a UNI-T UT333 digital thermo-hygrometer (humidity 0-100% temperature: -10°C...+60°C), error ±1°C/±5%. The wind speed was measured using a mini-anemometer HT-383, measurement accuracy ±1.5 m/s, measurement range 0...30 m/s. The substrate temperature was measured using an AMT-300 analyzer, temperature error ±1°C, measuring range from +9°C to +50°C.

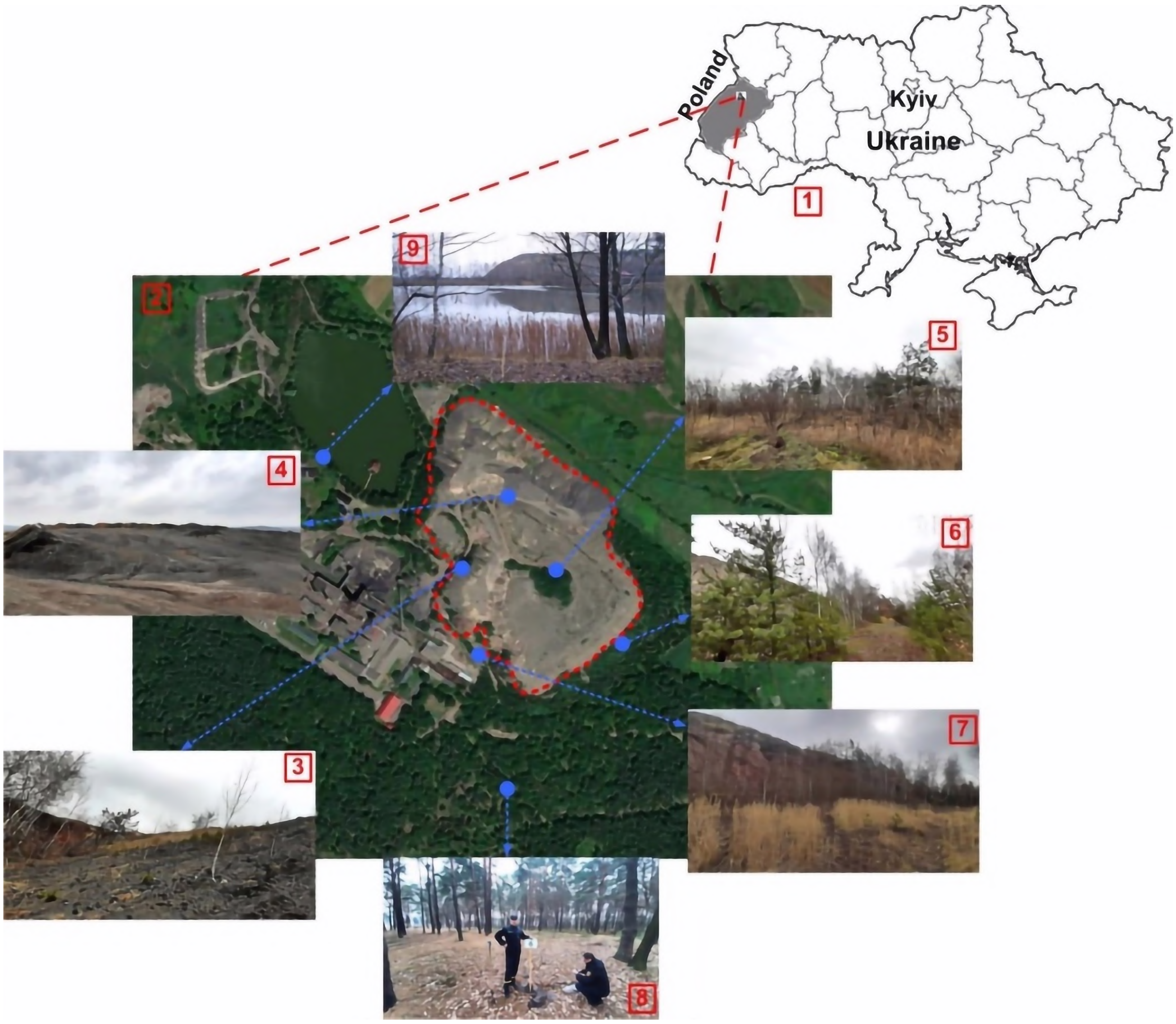

Figure 1. Location of the study site: 1 – map of Ukraine with the designation of the Nadiya mine; 2 – image of the waste heap of the Nadiya mine using GoogleMaps; 3-9 – sampling points.

3. Results and discussion

3.1. Radiation background research

The radiation background with distance from the waste heap was measured to study the impact of waste heaps on natural phytomelioration. The general characteristics of the studied areas are shown in table 1.

According to the radiation background studies of the Nadiya mine waste heap, it was found that at the level of 10 m from the foot of the heap and on the terraced slope (where there are numerous places of water erosion outlets, places of waste heap fire, fuel and lubricants drainage, household waste), the radiation power is significantly higher than in other areas, except for the top of the heap. Studies of the radiation background of the Nadiya mine spoil heap showed that the equivalent dose rate of photon ionizing radiation on the surface of the decaying heap is 0.42 μSv/h, which exceeds the permissible radiation background values established by the radiation safety standards of Ukraine (0.3 μSv/h). In addition to exceeding the permissible standards, the radiation background at the top of the waste heap at Nadiya mine also exceeds the background values for Sosnivka (0.12 μSv/h). It should be noted that the highest values of the equivalent

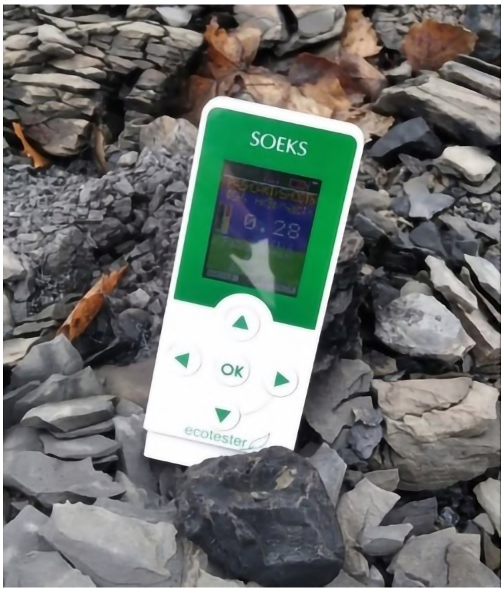

Figure 2. SOEKS environmental tester operation.

Table 1. Characteristics of the studied areas of the Nadiya mine waste heap.

Location	Radiation background, μSv/h	Lighting intensity, lux	Air humidity, %	Wind rate, m/s	Substrate temperature, °C
The foot of the heap	0.25	28350	82	3.6	5
Slope	0.18	30170	80	3.9	6
Terraced slope	0.29	32100	79	4.1	6
The foot of a terraced forest plot	0.21	25390	84	2.5	4
Top of the heap	0.42	34630	72	4.5	6
Control point 3 km from the waste heap	0.12	22480	83	1.6	5
Reservoir	0.17	–	–	–	–

dose rate were observed near the burning areas of certain parts of the waste heap and amounted to 0.21, 0.25, 0.29 and 0.42 μSv/h (figure 3). The lowest values were recorded in the forest area 3 km from the waste heap and near the man-made reservoir 2 km from the waste heap, which amounted to 0.12 and 0.17 μSv/h.

Figure 3. Results of burning certain areas of the waste heap at Nadiya mine (photo by A. Voloshchyshyn and P. Bosak)

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3.2. Modeling the spread of radiation background

Researchers say that burning waste rock can lead to an increase in the radiation background [22]. According to the studies, it was confirmed that the radiation power on the top and slopes of the Nadiya mine spoil heap, where the heap is burned, is much higher than in other areas [23]. The study of the radiation background of the investigated waste heap showed an average equivalent dose rate on the surface of the decaying waste heap of 0.27 μSv/h, which does not exceed the radiation safety standards but exceeds the background values for the region [24, 25]. The modeling of radiation background propagation in the edaphic horizons of the Nadiya mine waste heap is shown in (figure 4).

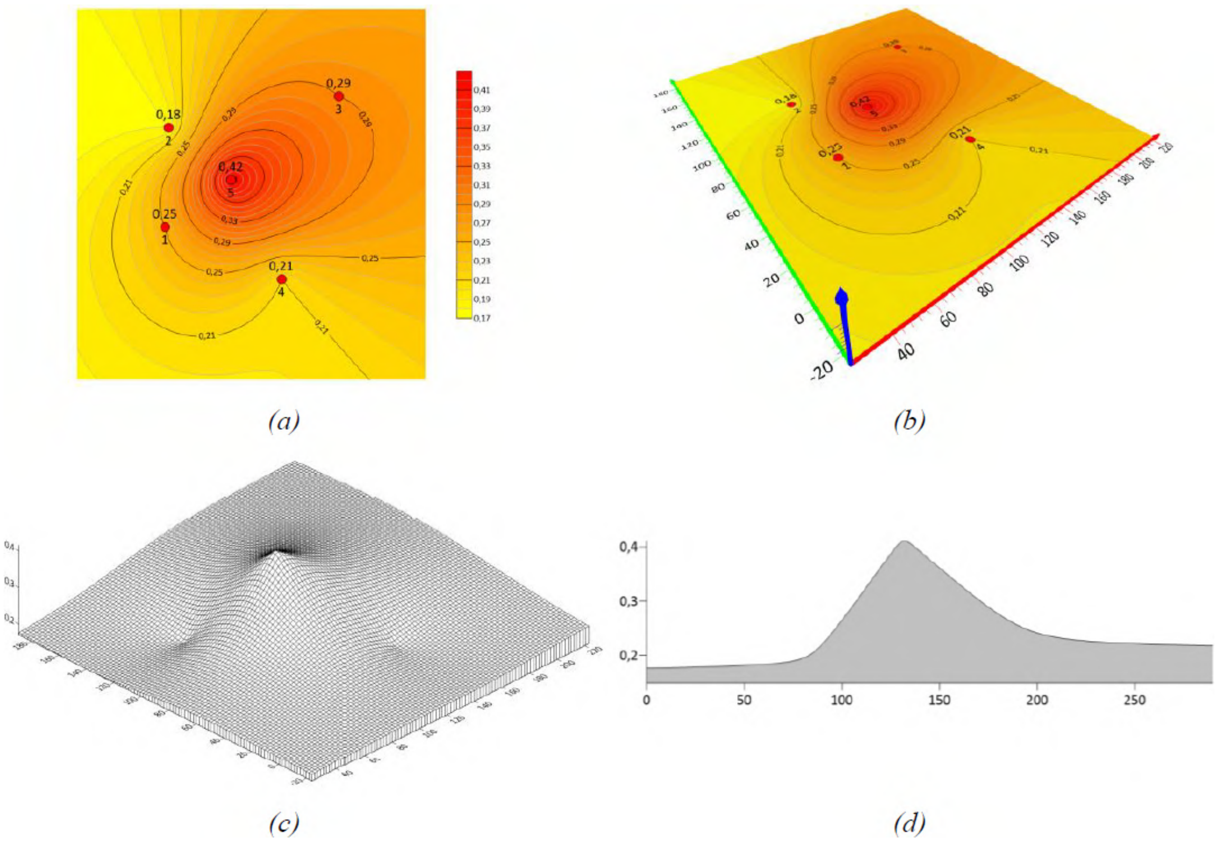

Figure 4. Radiation background propagation in the edaphic horizons of the Nadiya mine waste heap, μSv/h ((a), (b) – spread of the highest equivalent dose rate of photon ionizing radiation; (c), (d) – mine waste heap horizon 0-0.5 m).

The results of modeling the spread of radiation background are consistent with the data of phytocoenological studies. The slopes exhibit a multitude of instances of erosion caused by wind and water, fire-prone areas, release of household waste, fuel and lubricants, and high-intensity water erosion.

3.3. Influence of radiation background on the development of vegetation species composition in a coal mine

During the study of the spread of radiation background in the edaphic horizons of the Nadiia mine waste heap, a variety of species composition of the grass cover was observed, which was greater. Only single groups of Canada bluegrass (*Poa compressa* L.) are found in the grass cover. The smallest distance from the control site with virtually no anthropogenic impact

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(natural forest plantation with significant forest litter and Scots pine *Pinus sylvestris* L.) is characterized by the foot of the waste heap of the forest site. There are quite favorable growing conditions here. The projected cover of the grass cover is more than 65% and of the tree species more than 60%İn addition to the Canada bluegrass (*Poa compressa* L.), there are such plants as dandelion (*Taraxacum officinale* Webb. ex Wigg.), narrowleaf plantain (*Plantago lanceolata* L.) and other species. Narrow-leaved lupine (*Lupinus angustifolius* L.) and common broom (*Cytisus scoparius* (L.) Link.) also occur on the top and slopes of the waste heap. As for the tree species, silver birch (*Betula pendula* Roth.) 7-9 m high, Scots pine (*Pinus sylvestris* L.) 1-2 m high (up the slope and at the foot (forest zone) of the waste heap can reach 6-7 m high), and *Robinia pseudoacacia* L. – 3-6 m high. The following species grow sporadically: common hawthorn (*Crataegus monogyna* Jacq.), common dog rose (*Rosa canina* L.), goat willow (*Salix caprea* L.) – over 2-5 m high and pedunculate oak (*Quercus robur* L.) – 2-4 m high.

Thus, the models of dynamic or spatial distribution of vegetation, the relationship between vegetation and tree species and the impact of the radiation background, and the assessment of the human impact of the waste heaps at the Nadiia mine can be explained in terms of categories of directions and distances in the multidimensional feature space. However, to reduce the radiation background on waste heaps (especially where it reaches 0.27 μSv/h and above), we recommend planting vegetation and tree species (protective afforestation that reduces the spread of radionuclides) in the ecological and technogenic areas of the waste heap, because radiation has no borders.

4. Conclusions

Thus, the coal industry contributes pollutants to the soil, underground and surface water bodies, air and biota, creating a huge anthropogenic load on subsystems of natural objects. Coal mining and processing waste contains a large number of useful components. In accordance with the requirements of environmental safety and rational nature management, the most efficient way to deal with waste heaps is their complete elimination, but in modern society this way has almost no prospects of realisation, which is due to many economic reasons. That is why the development of new technologies related to environmentally safe and cost-effective disposal of waste heaps is of great importance today.

As mentioned earlier, the coal sector is a major problem for the coal industry and, consequently, for environmental protection. Taking into account the large number and high heterogeneity of waste heaps, as well as excessive radiation background values inherent in areas where rock combustion processes occur (0.21-0.42 μSv/h), any rational decision-making process, despite numerous studies of waste heaps, would not require more information about their composition, structure and location, but much more about appropriate solutions, namely closure of state-owned coal-fired power plants in Ukraine by 2035 (in accordance with the decision at the UN Climate Change Conference to phase out coal-fired power and gradually subsidize fossil fuels, reduce methane emissions by 30% by 2030, and stop deforestation), succession of the vegetation cover of waste heaps, and gradual introduction of natural phytomelioration on coal mine spoil heaps. Environmental safety studies of the natural and technological system of a mining district should be systematic and use a large number of methods and equipment, as their significant impact on the environmental safety of the region is obvious. The prospects for using the research results open up practical bases for the application of methods of the biological stage of reclamation (the so-called natural and artificial phytomelioration), which can reduce radiation and man-made pollution. Thus, continued research in mining areas will expand the range of methods needed to clean the atmosphere, soil, and water bodies from coal mine spoil heaps, while improving the environmental condition of the region. Studying and researching the process of restoring the natural vegetation cover of disturbed lands in the vicinity of coal mines and developing methods for restoring devastated landscapes is extremely important for all coal regions of Ukraine.

We believe that today (in difficult times for Ukraine), it is necessary to carry out reclamation and greening of waste heaps (spoil heaps) and reduce its anthropogenic impact on the urban environment in order to improve the environmental and technological safety of the area. By carrying out these projects, we can not only make rational use of the land damaged by mining, but also dramatically diminish the environmental harm caused by human activity in the state.

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Increasing the level of ecologically oriented logistics system in the waste management for territorial communities

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Increasing the level of ecologically oriented logistics system in the waste management for territorial communities

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Abstract. The characteristic features of nature protection policy in Ukraine are established. The significance of the solutions ecological logistics development for of municipal solid waste in order to reduce the negative impact on the environment has been confirmed. The significance of logistics for reducing the amount of waste and achieving its financial social and environmental goals is presented. The importance of environmental protection information and ecological knowledge as a special resource in innovative activity is emphasized. The characteristic qualities of the ecological approach in the field of logistics have been revealed.

1. Introduction

Given the increasing ecological challenges, it is imperative to examine the critical function ecologically aligned logistics systems have in improving waste management within local communities.

From an environmental perspective, logistics covers the entire life cycle of a product, including the possibility of recycling, the need to dispose of waste in various ways, and the choice of the most environmentally friendly transportation. Waste management logistics systems should include an analysis of the movement of waste from its generation in any production process to its transformation into marketable products or further disposal and safe storage in the environment. The formation of a waste logistics system requires the improvement of economic relations, involves the development of domestic production, state support for enterprises participating in the processes of implementing eco-friendly innovations in economic activities; revitalization of the commercial component and strengthening of the material and technical base.

This examination aims to explore the complex relationship between environmental policies, logistics innovations, and legislative conditions in Ukraine, emphasizing the paramount significance of this topic in today's ecological discussions. The goal is to perform a comprehensive analysis of the current waste management approach, illuminating sustainable practices that harmonize economic development with environmental protection. The results intend to furnish applicable understandings for policymakers, industry players, and the academic field, energizing the dialog towards viable environmental solutions.

2. Literature analysis and problem statement

Effective waste management in local communities involves a variety of strategies and processes that are complex and determined by unique local conditions such as geography, population density, and applicable regulations. This review synthesizes key insights from recent research to illustrate the challenges and solutions in this area.

Kartava, Kartavyi and Khrutba [1] draw attention to the importance of integrating environmental logistics into regional waste management programs, especially emphasizing the need to adapt European experience. They outline the key areas for implementing environmental logistics business strategies, including efficient use of resources, development of safe methods of waste disposal, and development of infrastructure to reduce their negative impact on the environment.

Popovych, Malyovanyi and Popovych [2] focus on the environmental challenges of rural areas, in particular the lack of necessary infrastructure for proper waste management. They emphasize the need to establish waste processing plants and develop a common logistics system to reduce environmental risks through integrated approaches to waste management.

Current research emphasizes the importance of taking into account local territorial characteristics, such as waste generation patterns and sorting dynamics, which critically affect the sustainability and working conditions at waste management facilities. In addition, a study conducted by Passarini et al. [3] in Emilia Romagna, Italy, found that rural areas demonstrate better environmental performance, which is explained by higher rates of separate waste collection and lower total waste generation compared to urban areas.

Predictive modeling is becoming a vital tool to inform the development of municipal waste management policies. By integrating socio-economic and demographic factors, such models allow for the development of tailored policy measures that reflect the diverse needs of different territorial levels [4].

Optimizing waste collection routes in communities not only reduces operational costs but also improves environmental outcomes. Bihun, Lytvyn and Oleksiv [5] demonstrate how strategic route planning significantly contributes to more efficient waste management. The introduction of smart technologies is playing a transformative role in waste management systems. Veloz-Cherrez et al. [6] discuss how systems equipped to monitor waste decomposition can optimize collection schedules and reduce environmental impact by providing real-time data.

Modern international experience offers many effective solutions to address the problem of accumulation of solid waste and the introduction of modern technologies for their implementation. The application of modern management methods involves the introduction of a logistics approach in the development of local waste management programs, which ensures the effective implementation of these programs and reduces the negative impact of waste on the environment. The implementation of the programs involves a wide range of stakeholders, which requires the use of new innovative management methods, such as crowdsourcing networks, as a mechanism for realizing the potential of the public.

The novelty of this study is the introduction of a conceptual model of an environmentally friendly innovative logistics system of waste management, which is integrated and comprehensive for territorial communities. The study focuses on three levels of management: strategic, tactical, and operational. This ensures the development and implementation of programs that include the regulation of production, processing, sorting and collection of waste. The key aspect of novelty is the change of priorities in the interrelationships of municipal solid waste management, the inclusion of environmental awareness and waste management culture of all stakeholders. This approach helps to reduce the negative impact on the environment, optimize waste management processes and efficiently use resources, which opens up new opportunities for creating sustainable and effective waste management systems.

3. Results and discussion

The implementation of a conceptual model of an environmentally safe innovative logistics system of waste management, as an integrated complex system of waste management for united territorial communities (here and after – UTC) (figure 1), is based on three levels of regional management – strategic, tactical, operational.

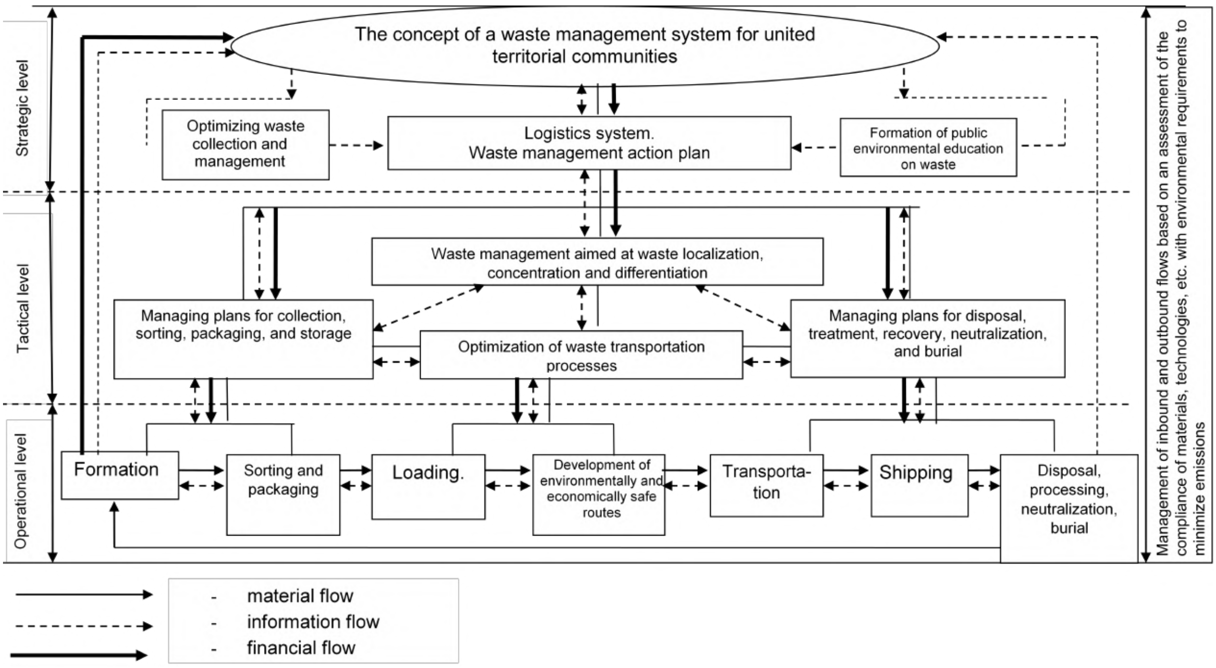

Figure 1. Components of the logistic approach to the waste management system concept for united territorial communities.

The strategic level is determined by compliance with the legislation of Ukraine. The Verkhovna Rada of Ukraine adopted the law "On Waste Management" [7], which will establish new transparent rules for the industry and allow the construction of a modern waste management infrastructure. This bill was developed on the basis of three EU directives – on waste, on waste disposal, and on industrial emissions.

The law provides for:

- introduction of the waste management hierarchy;
- introduction of the "polluter pays" principle;
- introduction of a system of extended producer responsibility, which establishes a requirement for packaging manufacturers to bear responsibility for the full life cycle of created packaging, batteries, accumulators, electrical and electronic equipment, etc.;
- creating an opportunity to attract investments in the construction of waste processing plants;
- introduction of strict European environmental standards for incineration and waste disposal operations in order to prevent harm to human health and the environment;
- the legal basis for short-term and long-term waste management planning;
- introduction of an electronic waste management information system to ensure transparency in the industry and avoid corruption risks, which will consist of open registers, modules for providing administrative services (issuance of documents online), reporting and analysis of static information [8, 9].

The law proposes to solve such problems as uncontrolled disposal of waste at landfills that do not meet environmental standards; fictitious waste processing, when in fact they are processed only according to documents; carrying out operations with waste without permit documentation.

The implementation of this law at the tactical level is possible due to the development and implementation of logistic systems of waste management with minimization of the impact on the environment. The main problems of the existing organization of waste management in the Zhytomyr region include:

- overestimation of costs for transportation due to the fact that the volume of waste to be removed is determined on the basis of theoretical norms of waste generation;
- a decrease in the quality of sanitary cleaning and an increase in the cost of services due to the fact that most often garbage trucks drive half-empty, since the payment for services for the transportation of solid waste is carried out in terms of volume;
- the increase in the number of unauthorized landfills due to the lack of centralized control over the process of transporting solid waste in cities contributes to the increase in the cost of maintaining the necessary sanitary and ecological standards of living in the city.

The advantages of using reverse logistics are protecting the environment from pollution, reducing the amount of household waste, minimizing costs and saving raw materials, materials, fuel and energy, increasing the environmental rating of the enterprise, forming recommendations and services for the purpose of making administrative decisions [10].

The final goal of implementing a logistics approach is the rapid collection of logistics data for the systematic operation of services.

The novelty of the concept of the logistic approach in the management of the waste management system consists in the change of priorities in the distribution of relationships in the management of waste management and includes the formation of environmental awareness and the culture of waste management of all stakeholders. The scheme of the proposed logistic system of functioning of the regional waste management plan for territorial communities with the inclusion of a coordinating agent for waste management is shown in figure 2.

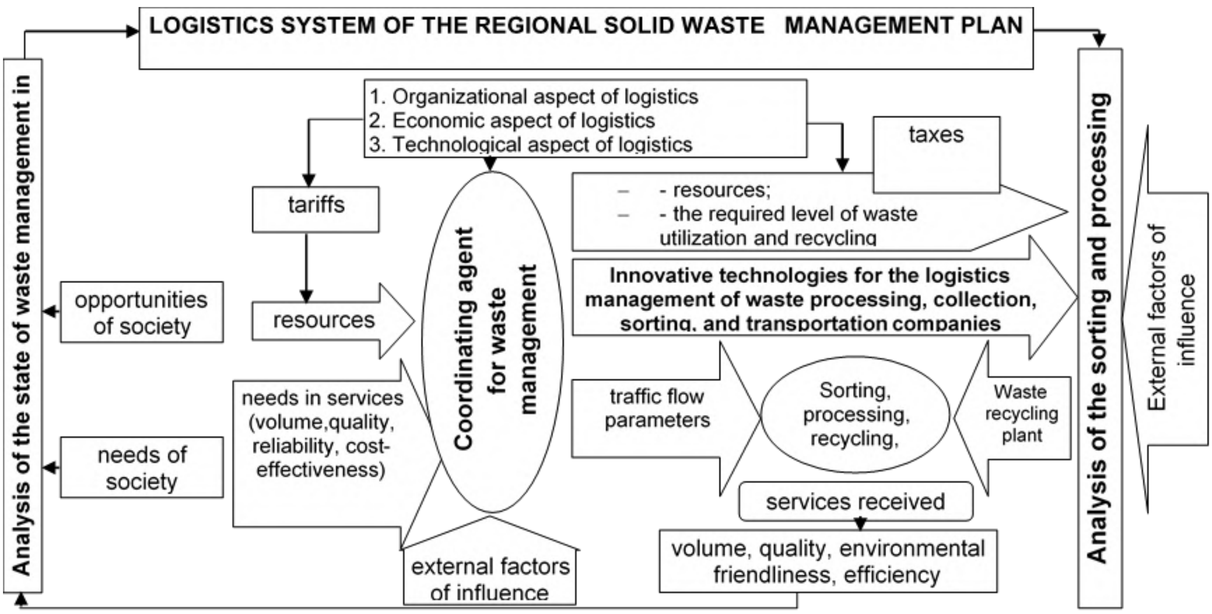

Figure 2. Diagram of the logistics system of the waste management process for territorial communities.

The logistics concept in waste management involves the presence of a coordinating agent and involves the management of knowledge that is applied to new business lines implemented in certain program plans. The coordination agent provides management of all logistics flows of solid waste – financial, material, informational (figure 3). The operation of the system on the scale of this model is focused on stability and duration.

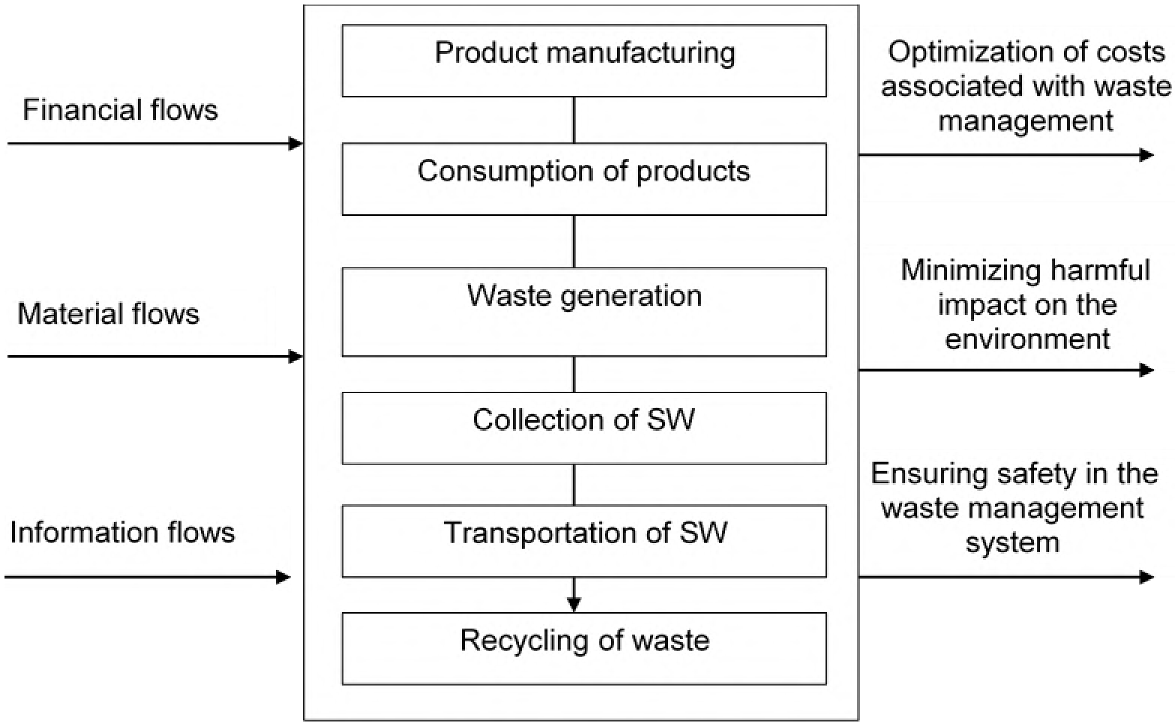

Figure 3. Flows of solid waste in the management of logistics.

The implementation of an ecological logistics business strategy to reduce overall emissions in the management of regional waste management programs for each territorial community should go through four stages:

1) strategic decisions, which are made based on the results of the analysis of the amount of waste, the location and assessment of the potential of waste transport enterprises, waste enterprises, waste storage and disposal sites;
2) the tactical level of planning communal and commercial decisions regarding the production of secondary waste processing products, waste recycling and distribution of finished products, creation of a structure of partnership relations between the processing company and its suppliers, distributors and customers;
3) operative decisions on coordination of the terms of implementation of planned decisions regarding production from resource-valuable raw materials and distribution, redistribution of links to separate material flows of waste and determination of the speed of rotation of the inventory in places of storage or sorting of waste;
4) functional solutions related to the management of material and technical resources during the implementation of planned solutions of the waste management program.

The logistics concept of waste management combines the management of the waste life cycle from generation and accumulation to transformation into a marketable product or safe storage in the environment. The logistics of waste management is influenced by the following factors: the amount of waste generation; basic professional ideas; prevailing scientific and technical concepts; regulatory framework; attitude of the state; attitude of the community and its economic opportunities. The Coordinating Center is assigned for the organization of the waste accounting system created as a result of product consumption, namely: waste accounting; analysis of their morphological state at all stages of their life cycle; collection of solid waste in eco-containers or at points of reception of secondary raw materials; transporting them for processing with subsequent transformation into a finished useful product.

The formation of the material flow of waste is shown in figure 4.

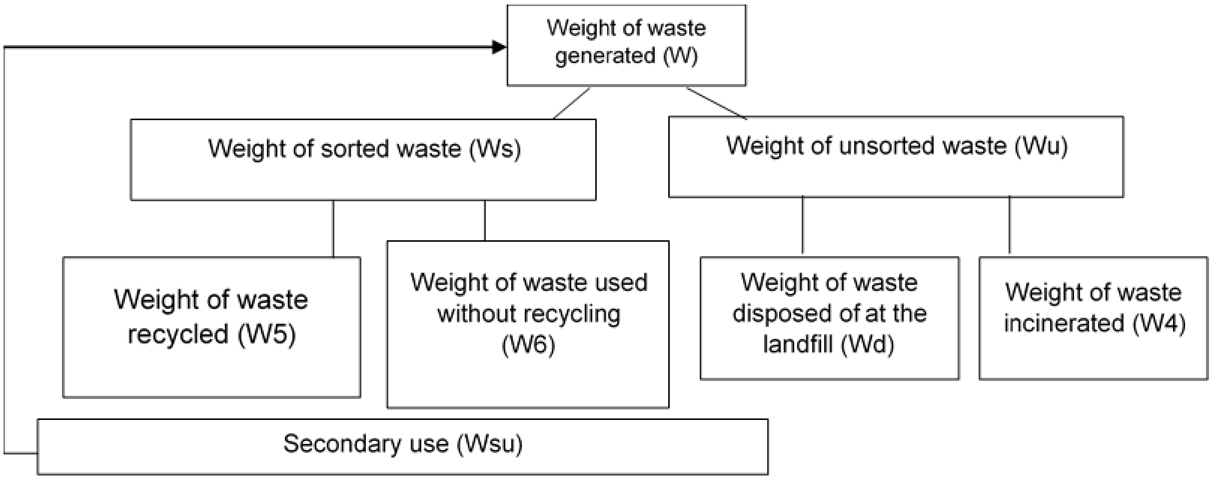

Figure 4. Flows of solid waste in the management of logistics.

Material flows of solid waste can be represented by corresponding sets:

$$W_{SW} = (W_{met}, W_{glass}, W_{other\,waste}, W_{PET\,plastic products}, W_{paper}), \tag{1}$$

where W_{met} is material flows of waste metal products, which have the form of a set:

$$W_{met} = (W_{tin\,cans}, W_{cans}, W_{metal\,covers}), \tag{2}$$

where $W_{tin\,cans}$ is material flows of tin can waste, W_{cans} is material flows of canning can waste, $W_{metal\,covers}$ is material flows of metal lid waste; W_{glass} is material flows of glass waste, which have the form of a set:

$$W_{glass} = (W_{glass\,bottles}, W_{glass\,products}), \tag{3}$$

where $W_{glass\,bottles}$ is material flows of glass bottle waste, $W_{glass\,products}$ is material flows of waste glass products.

$W_{other\,waste}$ is material flows of waste of other waste, which have the form of a set:

$$W_{other\,wastes} = (W_{organic\,species}, W_{debris}, W_{wood}, W_{leaf}, W_{textile}), \tag{4}$$

where $W_{organic\,species}$ is material flows of waste organic waste, W_{debris} is material flows of construction waste, W_{wood} is material flows of wood waste, W_{leaf} is material flows of leaf waste, $W_{textile}$ is material flows of textile waste.

$W_{PET\,plastic products}$ is material flows of waste plastic products, which have the form of a set:

$$W_{PET\,plastic products} = (W_{containers}, W_{bottles}, W_{container}, W_{bottles}, W_{plastic\,covers}, W_{caps}), \tag{5}$$

where $W_{containers}$ is material flows of waste packaging materials, $W_{bottles}$ is material flows of bottle waste, $W_{container}$ is material flows of container waste, $W_{bottles}$ is material flows of bottle waste (cosmetic and household chemicals), $W_{plastic\,covers}$ is material flows of waste plastic covers, W_{caps} is material flows of waste caps.

W_{paper} is material flows of paper waste , which have the form of a set:

$$W_{paper} = (W_{newspapers,magazines}, W_{cardboard\,boxes}, W_{paper\,packaging}, W_{wastepaper}), \tag{6}$$

where $W_{newspapers,magazines}$ is material flows of newspaper, magazine waste, $W_{cardboard\,boxes}$ is material flows of cardboard box waste, $W_{paper\,packaging}$ is material flows of paper packaging waste, $W_{wastepaper}$ is material flows of paper waste.

Management of material flows of waste includes:

- ensuring effective collection of waste in places of their greatest concentration;
- determination of the optimal transportation route, taking into account the possibilities of their sorting.

The movement of the material flow of waste in the logistic scheme of handling waste is depicted in figure 5.

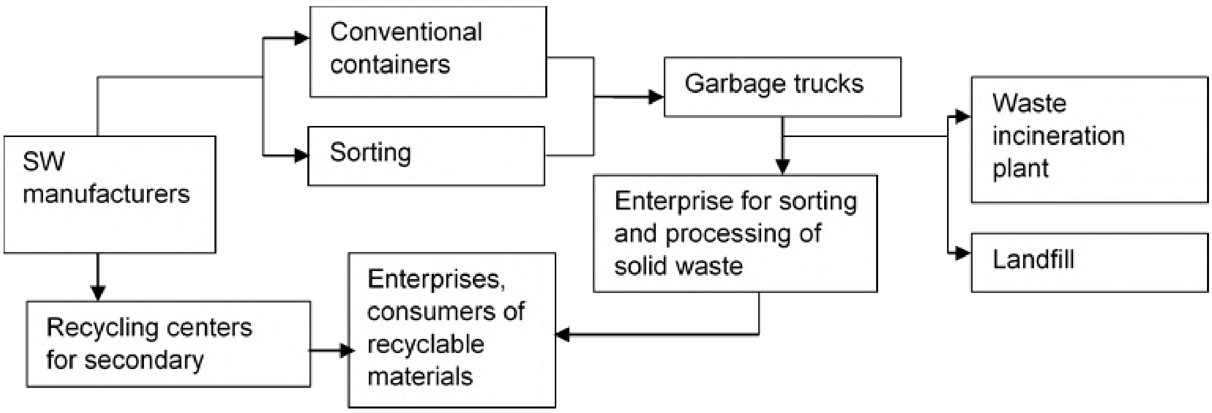

Figure 5. The movement of the material flow of waste in the logistic scheme of the management of solid waste.

The experience of implementing logistics concepts in the regional management of mechanisms of secondary resources to optimize the interests of suppliers and consumers and the ways of applying logistics chains for the organization of the movement of secondary raw materials are discussed in publications [11, 12].

The logistics system in waste management programs consists of two logistics subsystems. The first is the logistics system of direct waste mass movement, which includes the processes of generation, collection, transportation, utilization, and disposal. The second is a logistical program management system, which includes the processes of agreement, selection and implementation of program projects.

The tasks of the logistics system in waste management programs include management of material flows of waste and resources of the program, consulting of financial flows and management of information flows.

The logistics chain of solid waste management is implemented in the integrated logistics concept of the settlement of UTC and includes the following links: primary sorting of municipal solid waste, waste collection, transportation of solid waste, secondary sorting of waste, burial of waste at a landfill and its incineration, processing of solid waste to obtain secondary raw materials and its implementation. The task of optimizing the logistics system is to redistribute material flows in such a way as to reduce waste flows for landfill or incineration and increase flows of secondary use or recycling.

During the operation of logistics systems in the waste management of the region to reduce the total emission of waste, it is important to take initiatives at the lower level of the decision-making hierarchy determined by both economic and environmental benefits. Functional-level solutions focus on increasing fuel efficiency for waste transportation, optimizing vehicle routing, and saving energy at waste collection and sorting sites. The main task is to integrate environmental principles into the strategic planning of logistics and coordination of environmental management at all four levels of decision-making, which will allow achieving the mission of the program at every step of its implementation.

To enhance the management of waste material flows across different territorial areas, we need to address the challenge of uncertain future costs. These costs are related to waste management processes and the utilization of production resources. It's crucial to consider the unique aspects of technological processes and the production resources available to economic entities. Our goal is to develop a production program that minimizes environmental damage during the operation of the waste management system. To build economic-mathematical models, we introduce the following notation [11].

Known quantities:

- n – the volume of solid waste that can be formed in UTC;
- j – number of a separate type of solid waste $j = \overline{(1, n)}$;
- m – the number of types of production resources of business entities in the waste management system;
- i – number of a separate type of production resources $i = \overline{(1, m)}$;
- a_{ij} – regulatory costs ith of the production resource for collection, sorting, transportation, processing, disposal of the unit of the jth type of solid waste;
- b_i – available volumes of production resources of the ith type of business entities in the waste management system;
- c_j – the variable part of the cost of the processes of handling the solid waste unit of the jth type of waste, without taking into account the cost of consumed production resources;
- x_j^{min}, x_j^{max} – respectively, the lower and upper limits of the amount of waste of the jth type, which are generated in a separate territorial community;
- y_i^{min}, y_i^{max} – respectively, the lower and upper limits of the volume of production use of the ith resource of business entities in the waste management system;
- v_i^{min}, v_i^{max} – respectively, the lower and upper limits of the volume of acquisition of additional production resources of the ith type of business entities in the waste management system;
- w_i^{min}, w_i^{max} – respectively, the lower and upper limits of the volume of realization of surplus production resources of the ith type of business entities in the waste management system.

Unknown quantities (controlled variables):

- x_j – the amount of waste of the jth type, generated in a separate territorial community;
- y_i – volume of production consumption of the ith resource of business entities in the waste management system;
- v_i – volume of procurement of additional production resources of the ith type of business entities in the waste management system;
- w_i – the amount of excess production resources of the ith type of economic entities in the waste management system;

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- z – total costs of business entities in the waste management system in its variable part.

Uncontrolled parameters:

- p_j – market price of a unit of the jth type of solid waste;
- q_i – the market price of a unit of the ith production resource of business entities in the waste management system.

In deterministic conditions, the values of uncontrollable parameters at the moment of decision-making are considered known. If there are risks, they are considered as random variables with known statistical characteristics.

Dependencies between known, unknown quantities, and uncontrollable parameters:

- volumes of generated waste, as well as volumes of production use, acquisition of additional, or sale of surplus production resources of business entities in the waste management system, must meet predetermined limits:

$$x_j^{(min_j,max_j(1,n))}; \quad y_i^{(min_i,max_i(1,m))}; v_i^{(min_i,max_i(1,m))}; \quad w_i^{(min_i,max_i(1,m))};, \tag{7}$$

- the production use of resources of business entities in the waste management system is determined by the features of the technological processes of collection, sorting, transportation, processing, disposal of solid waste:

$$y_i = \sum_{j=1}^{n} a_{ij} x_j, \quad i = \overline{1,m};, \tag{8}$$

- a balance must be maintained between the formation of solid waste and the use of production resources of economic entities for the processes of collection, sorting, transportation, processing, and disposal of solid waste:

$$b_i + v_i = y_i + w_i, \quad i = \overline{1,m};, \tag{9}$$

- the costs of economic entities in the waste management system are determined by the sum of the losses of territorial communities caused by the amount of generated waste and the costs of economic entities for the use of production resources:

$$\begin{aligned} z = \sum_{j=1}^{n}(p_j + c_j)x_j + \sum_{i=1}^{m} q_i y_i + \sum_{i=1}^{m} q_i w_i \to \min, \\ \sum_{j=1}^{n} a_{ij}x_j - y_i = 0, \quad i = \overline{1,m}, \\ y_i - v_i + w_i = b_i, \quad i = \overline{1,m}, \\ x_j^{\min} \le x_j \le x_j^{\max}, \quad j = \overline{1,n}, \\ y_i^{\min} \le y_i \le y_i^{\max}, \quad i = \overline{1,m}, \\ v_i^{\min} \le v_i \le v_i^{\max}, \quad i = \overline{1,m}, \\ w_i^{\min} \le w_i \le w_i^{\max}, \quad i = \overline{1,m}. \end{aligned} \tag{10}$$

The model is a linear programming problem, and the widely used MS Excel package can be used to find its solution.

To implement the production program of the UTC for the implementation of a logistics system for waste management, it is advisable to form a system for managing information logistics flows according to the service model presented in figure 6. The information system ensures the collection, transmission and processing of information received by business entities in the waste

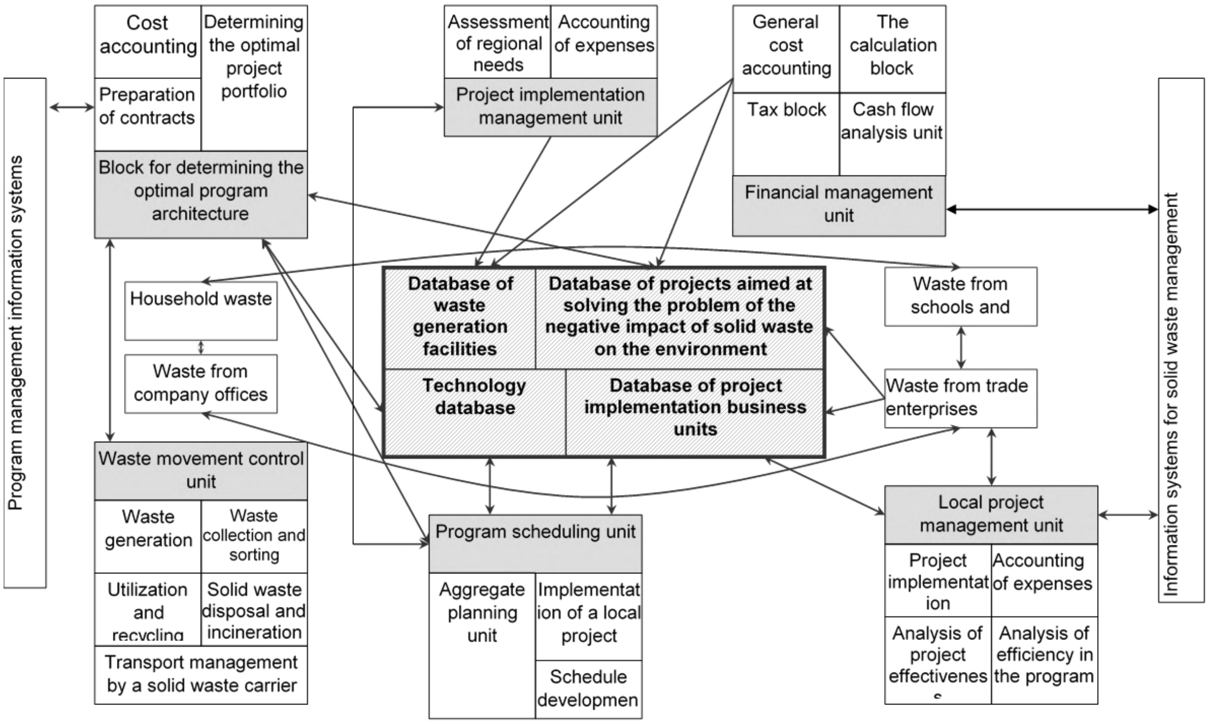

Figure 6. Service model of electronic waste management information system for territorial communities.

management system. In the system, information processing tools are placed inside information flows to achieve the greatest efficiency of its use. At the same time, the process includes the search for ensuring the level of logistics activity, at which the costs for the implementation of the technological processes of collection, sorting, transportation, processing, disposal of solid waste are minimal.

Management of information flows includes the exchange of information about the composition and structure of the material flow of waste, the value of emissions during certain processes related to the formation, storage, transportation and disposal of waste. Exchange of information between the heads of the UTC during the implementation of the production program and project managers, between the formation of the solid waste and their management processes, between all interested parties, including residents of the community and region [13].

Information has quantitative and qualitative characteristics and, as a rule, is related to material and financial flows and can follow them synchronously, or can be separated. Using the model will increase the flexibility of the logistics system, improve its scalability and stability, and reduce the time to respond to changes [14, 15].

This logistics system allows to improve the functioning of organizational business processes of interaction of the community, authorities and communal enterprises in the removal, transportation, collection of waste and to implement logistics technologies in practical activities. The result of the interaction of all interested parties is the creation of an effective system of collection, sorting, transportation and disposal of waste, characterized by the achieved level of ecological and economic efficiency and environmental safety. Therefore, comparing the parameters of the actual volume of services with the required parameters, determine the logistical effect of the waste management system and the use of secondary resources.

4. Conclusion

A systematic model of solid waste management for territorial communities was developed, taking into account the interests of stakeholders and a morphological model of a regional waste management program. The model allows to identify ways of waste management (prevention of generation, reduction of waste, optimization of waste flows by restoring their value, reuse, recycling, disposal and control over waste disposal facilities) for territorial communities to prevent the harmful effects of waste on the environment and public health.

Methods and tools for implementing a regional waste management program based on a logistics approach have been developed, which involves the formation of an environmentally oriented logistics system for managing waste management programs and the development of logistics models for municipal waste transportation processes.

The results include:

- a business strategy for the implementation of environmental logistics to reduce overall emissions for the management of regional waste management programs for a particular UTC, which provides for the sequential implementation of stages – strategic decision-making, formation of the tactical level, implementation of operational and functional solutions;
- a schematic model of the logistics system for the functioning of the regional waste management plan for the UTC with the inclusion of a coordinating agent for waste management to ensure the management of all logistics flows of the solid waste – financial, material, information. and allows the formation of projects, technologies and measures to reduce the amount of waste, its recovery, recycling or disposal in a complementary manner;
- an economic and mathematical model for determining the production program of the UTC for the implementation of the logistics system of waste management, the optimization of which allows redistributing material flows of solid waste in individual UTCs in the implementation of waste management processes and production resources, based on the characteristics of technological processes and available production resources of business entities while minimizing environmental damage;
- a service model of an electronic information system for managing logistics waste flows to implement the production program of an UTC. Information flow management includes the exchange of information on the composition and structure of the material flow of waste, the value of emissions from certain processes related to the generation, storage, transportation and disposal of waste. Information exchange between UTC managers in the implementation of the production program and project managers, between the formation of solid waste and its management processes, between all stakeholders, including community residents;
- a set of criteria for a comprehensive assessment of the impact of the system of transportation, disposal and processing of solid waste is proposed for a comprehensive assessment of the impact of the system of transportation, disposal and processing of solid waste is proposed, which includes material and technical criteria, criteria of professional requirements, financial and economic criteria, environmental criteria and social criteria. Each group of criteria is characterized by a set of local criteria, which allows the choice of the business structure of the carrier for the transportation of solid waste while optimizing the logistics system of waste management;
- the conceptual model of a regional waste management program based on the logistics approach includes sets of relevant sets: strategic goal (M_i), resources (R_i), finance (F_i) and information (I_i) and involves the involvement of a coordinating agent as a separate business entity to manage the waste management system, which manages all waste generated in a certain territory and allows the formation of projects, technologies and measures to reduce the amount of waste, its recovery, recycling or disposal with the addition of one or more

of the following Implementation of the model for UTCs involves increasing the efficiency of waste collection, transportation and storage.

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