Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: O S Pylypenko and T H Kramarenko 2024 *J. Phys.: Conf. Ser.* **2871** 012004

Structural and functional model of formation of STEM-competencies of students of professional higher education institutions in mathematics teaching

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Abstract. This study focuses on the vocational preparation of learners in professional pre-higher educational establishments. The primary objective is to provide a theoretical foundation for, construct, and empirically evaluate the efficacy of a structural-functional paradigm for cultivating STEM proficiencies among students in these institutions through mathematics instruction. The pedagogical experiment corroborated the research postulate that attaining advanced STEM competencies in mathematics among professional pre-higher education students can be facilitated through a learning model that incorporates specific pedagogical conditions: motivating and stimulating students to engage in educational, cognitive and research activities in mathematics through engagement in cooperation and the use of individual and group coaching; implementation of STEM projects in mathematics teaching; usage of ICT to ensure visibility and research orientation of mathematics teaching. The experimental outcomes and accompanying educational resources have enabled a comprehensive analysis of the challenges associated with implementing STEM methodologies in mathematics instruction. This article aims to elucidate the key attributes of the devised structural-functional model and evaluate its implementation efficacy, with particular emphasis on the application of the authors' developed pedagogical support materials.

1. Introduction

STEM education is one of the most important areas of education reform in Ukraine. The development of STEM competencies among young people can help bridge the gap between education and the demands of modern life. The implementation of STEM education will help to prepare a professional armed with innovative teaching technologies, practical personal experience that will satisfy the social order of society [1]. In the context of integration and mobility, the educational paradigm requires new approaches to learning, including mathematics. It is important to search for innovative methods that will help to form a personality capable of solving complex problems. Motivating and stimulating students to educational, cognitive and research activities in mathematics teaching are considered as important pedagogical conditions in the context of the general problem of forming STEM competences of professional junior bachelors [2].

Journal of Physics: Conference Series **2871** (2024) 012004 doi:10.1088/1742-6596/2871/1/012004

1.1. Theoretical foundation
The conceptual frameworks and practical implementations of STEM education in Ukraine have been explored by various researchers [3–7]. Contemporary challenges in STEM education and the development of STEM project roadmaps are addressed in the handbook by Polihun et al. [8].

Pedagogical models centered on fostering STEM competencies in teacher training are presented by Balyk et al. [9] and Valko and Osadchyi [10,11]. Kuzmenko [12] dedicates significant attention to advancing STEM education within physics instruction.

Dynamic mathematics systems, particularly GeoGebra, are examined as engineering instruments by several scholars [13–15]. Kramarenko et al. [16] elaborate on the features of the GeoGebra 3D Calculator mobile application, which incorporates augmented reality to enhance mathematics teaching methodologies through cloud technologies.

Kuzmich et al. [17] investigate methodologies for studying metric spaces' geometric properties. They propose constructing analogues in two-dimensional and three-dimensional Euclidean arithmetic spaces to geometrically interpret the linear and planar arrangement of metric space points. The GeoGebra 3D dynamic geometric environment is recommended for concept visualization.

The application of immersive technologies in education, particularly within the STEM context, has been extensively researched [18–30].

STEM competencies are defined as a dynamic system encompassing knowledge, abilities, skills, thought processes, values, and personal attributes that foster innovative capacity. These competencies encompass the ability to tackle complex issues, develop critical thinking, creativity, organizational aptitude, emotional intelligence, and cognitive adaptability. Teamwork, decision-making, and effective interaction skills are also crucial.

However, a review of scientific literature reveals a scarcity of research on developing STEM competencies among professional college students. There is also limited exploration of higher education institutions' faculty involvement in enhancing training quality through STEM education.

An analysis of scientific sources and pedagogical practices has unveiled several contradictions in modern education:

(i) A disparity between the extensive domestic and international experience in implementing STEM education at the secondary level and the inadequate recognition of its necessity and relevance for professional junior bachelors.

(ii) A mismatch between the expected STEM competency levels of professional higher education graduates and their actual attainment.

(iii) A lag in curricular updates and methodological support for professional junior bachelors, despite the need for innovation driven by digitalization and European integration processes.

1.2. Article aims and objectives
The significance of this research is underscored by the swift progression of STEM education, alongside transformations in economic landscapes, technological infrastructures, and organizational structures. These changes are reshaping the knowledge and skill requirements for professional junior bachelors.

This article's primary objective is to elucidate the distinctive characteristics of the structural and functional model of formation of STEM-competencies of students of professional higher education institutions in mathematics teaching and to assess its implementation efficacy. Particular emphasis is placed on the application of the authors' custom-developed instructional and methodological resources.

Journal of Physics: Conference Series **2871** (2024) 012004 doi:10.1088/1742-6596/2871/1/012004

2. Results

Based on a comprehensive review of scientific and pedagogical literature, as well as educational practices, the authors have refined the conceptualization of STEM competencies for students in professional higher education institutions.

STEM competencies are characterized as an integrated personal construct, manifesting through the development of several key components:

- Mathematical proficiency
- Information and communication technology skills
- Foundational competencies in natural sciences and technology
- Project management and technological aptitude
- Soft skills, with a particular emphasis on critical thinking

The research team conducted an analysis of professional higher education standards across various disciplines, including Information, Library and Archival Affairs (029), Finance, Banking, Insurance and Stock Market (072), Accounting and Taxation (071), Business and Trade (076), and Food Technologies (181). This analysis identified competencies that students can develop through STEM disciplines, particularly mathematics. General STEM-related competencies include the ability to apply knowledge practically, utilize information and communication technologies, and effectively search, process, and analyze information from diverse sources.

For instance, specialty-specific competencies for students in Finance, Banking, Insurance and Stock Market (072) that align with STEM principles include:

- Utilizing theoretical and methodological tools from finance, economics, mathematics, statistics, law, and other relevant disciplines to address complex financial, banking, and insurance challenges
- Employing modern information systems and software for data acquisition and processing in finance, banking, and insurance
- Facilitating effective communication between specialists and service users in the financial sector

The study revealed that addressing existing contradictions is feasible through the establishment of specific pedagogical conditions, namely:

- motivating and stimulating students to engage in educational, cognitive and research activities in mathematics through engagement in cooperation and the use of individual and group coaching
- implementation of STEM projects in mathematics teaching
- usage of ICT to ensure visibility and research orientation of mathematics teaching

Three groups of external factors influencing STEM education actualization were identified:

1. Societal demand for highly qualified STEM professionals
2. Advancements in information, communication, and STEM technologies, including the development of specialized and adapted teaching tools for mathematics
3. Methodological considerations, encompassing teaching principles, fundamental learning organization approaches, and the modernization of instructional technologies and methods

The authors have developed and theoretically substantiated a structural and functional model of formation of STEM-competencies of students of professional higher education institutions in mathematics teaching (figure 1), grounded in scientific concepts of educational goals, objectives, and content [2]. The model's effective implementation is predicated on various approaches to learning, including project-based, research-oriented, competency-focused, activity-centered, personality-oriented, cognitive, synergistic, differentiated, and systematic methodologies. Educators are advised to adhere to principles such as scientific rigor, accessibility, developmental appropriateness, integration, cognitive engagement, individuality, research and practical orientation, theory-practice interconnections, learner independence and activity, interactivity, and metacognitive awareness throughout the instructional process.

The structural and functional model of formation of STEM-competencies of students of professional pre-higher education institutions in mathematics teaching is comprised of four interconnected components: target, content, activity, and diagnostic blocks.

The target block delineates the primary objective: cultivating STEM competencies among students in professional pre-higher education institutions through mathematics instruction.

The content and activity blocks elucidate the process of developing students' STEM competencies in mathematics education. These blocks encompass:

- The conceptual framework of students' STEM competencies
- Pedagogical conditions conducive to competency development
- Educational resources and methodologies
- Instructional approaches and formats

The diagnostic block outlines assessment tools based on carefully crafted criteria:

- Value-motivational
- Creative and active
- Cognitive
- Reflective-evaluative

These criteria serve as indicators for evaluating the formation of students' STEM competencies. The model employs a four-tiered classification system to gauge competency levels:

1. High
2. Sufficient
3. Intermediate
4. Elementary

In teaching mathematics to first- and second-year students of professional pre-higher education institutions using STEM approaches, it is advisable to follow the curriculum for grades 10-11 and its coverage in modern textbooks. Textbooks of the standard level were used in the teaching, in particular, by Merzliak et al. [31].

The authors made extensive use of the visualizations developed by Mathematics in STEM [13] to visualize abstractions using the GeoGebra dynamic mathematics system [32].

In order to determine what motivates college students to study mathematics, what they know about STEM education, and the use of ICT in teaching mathematics, it is advisable to conduct a survey to determine their level of motivation through STEM education. The analysis of the study results makes it possible to analyze not only the levels of students' motivation in learning mathematics, but also to establish that one of the important pedagogical conditions for the effective implementation of STEM education is to motivate and stimulate students to engage in

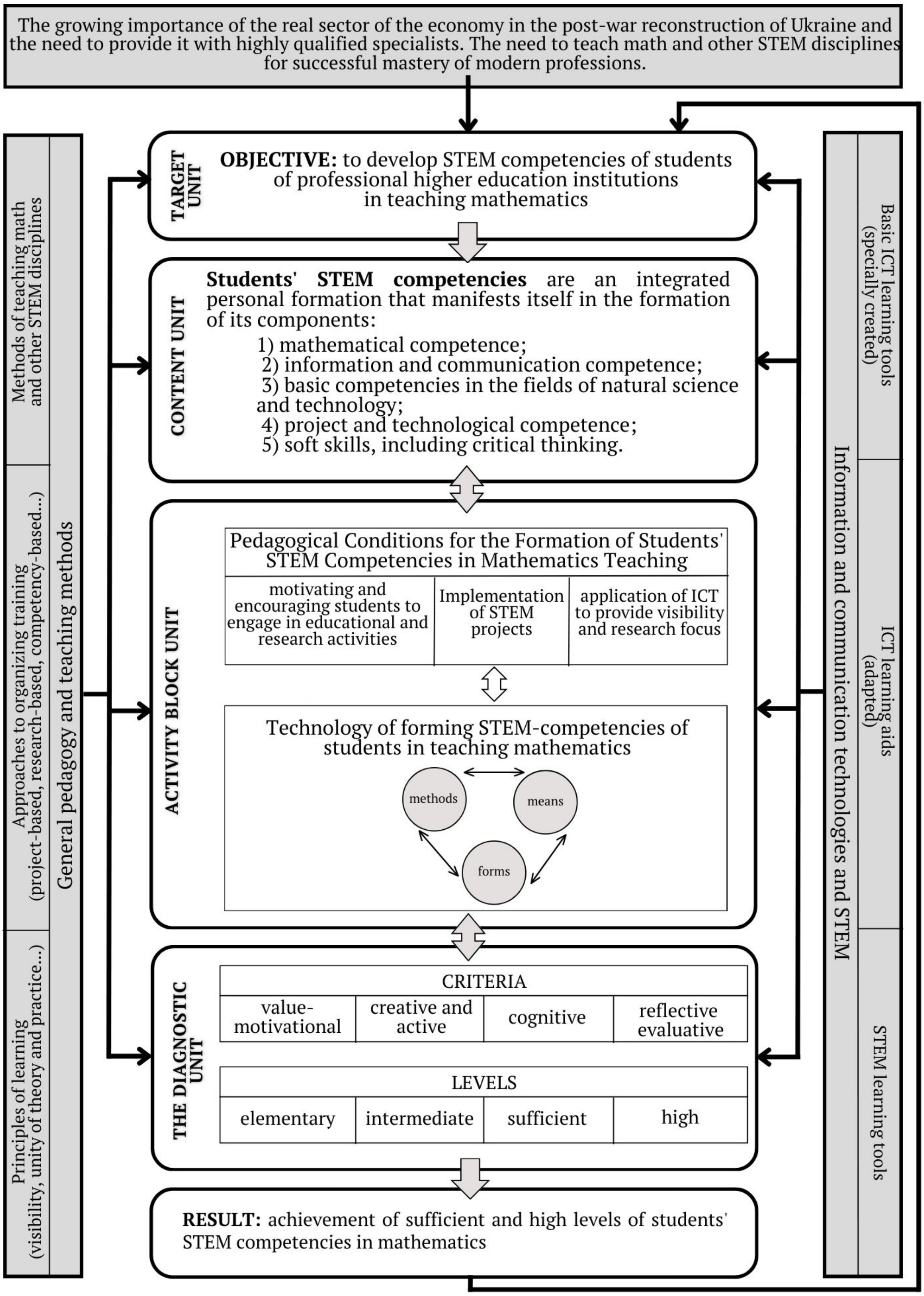

Figure 1. Structural and functional model of formation of students' STEM competencies in mathematics teaching

educational, cognitive and research activities in learning mathematics through engagement in cooperation and the use of individual and group coaching.

Here are the examples from our experience of motivating and stimulating students to engage in educational and research activities in mathematics. The most important thing for motivating students to do research is the personal significance of the chosen task for each of them. For example, when studying the elements of mathematical statistics, it is advisable to offer the following task.

1. Find out the ratio of a student's height to his/her weight. Using the Coutel formula, calculate whether the student's mass corresponds to his height. To do this, divide the weight measured in kilograms by the square of the height measured in meters. If the ratio is less than twenty, then weight needs to be gained. If the value of the calculated value is between 20 and 23, then the weight is normal. For those students whose calculated ratio is greater than 24 but not greater than 29, it is advisable to lose weight.
2. Investigate the body mass index of your own family members, and conclude how balanced the family's diet is. The project theme can be formulated more broadly – Math in the Kitchen.
3. How is mathematics, in particular statistics, used in agriculture, in the transportation industry, in construction, and in the student's future profession?
4. How efficiently is the garden or garden plot, if any, used by your family?

Considering the methodology of forming students' STEM competencies in mathematics, we distinguish the following main areas of STEM approaches:

- development and implementation of educational projects, including STEM projects that can be transdisciplinary;
- conducting binary and integrated classes that connect mathematics with other academic disciplines, including computer science, physics, economics, and statistics;
- use of dynamic mathematics systems, such as GRAN and GeoGebra, and other engineering tools for graphing functions, solving equations, inequalities, visualizing abstractions, etc;
- application of software tools for solving problems requiring statistical data processing;
- use of augmented reality;
- introduction of research tasks and applied tasks into the content of training.

Success in STEM mathematics education for finance students depends on the implementation of modern methods and pedagogical innovations. One of the key aspects is the integration of mathematical concepts into financial disciplines, that allows students to see the connection between theory and practice. Let's look at some examples of using educational projects as a basis for implementing STEM education in teaching mathematics to students of professional colleges. An example may be the use of mathematical models for risk analysis and financial decision-making, calculating interest rates and loans, studying investment strategies and trading operations.

Bank employees and citizens who keep money in a bank at interest or take out a loan deal with interest calculation formulas. Therefore, the user needs to familiarize himself with the lending terms of different banks in advance and be able to assess which bank is the most profitable to take out a loan from. The practical result of the project can be a report on the banks available in the region on the effectiveness of taking out a cash loan, a loan for a new home or a car, etc.

We have successfully engaged college students in the STEM project "Creating a 3D hologram". A hologram is a projection of an image of an object from a plane into three-dimensional space. This creates the illusion of three-dimensionality, since a person does not see the objects themselves, but only their light images. The proposed project is interdisciplinary.

In the math class, while studying the topic “Sections of polyhedra,” students were asked to make a model of a regular cut quadrilateral pyramid. Plastic plates were the material for the model. First, students made markings on the plate, then cut and glued the model (figure 2). To check the work, they opened the finished 3D hologram video on their phones and placed the inverted model on top.

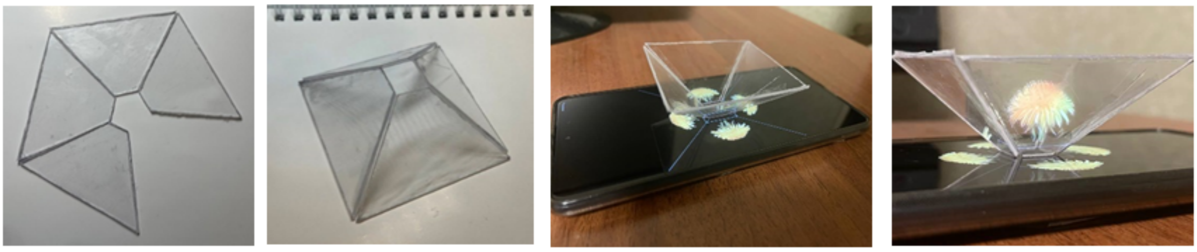

Figure 2. Photo for the Hologram project.

Based on the evaluation results, the following enhancements have been incorporated into the mathematics curriculum for professional pre-higher education institutions:

- Diverse educational formats, including ICT integration, STEM projects, STEM quests, web conferences, blogs, websites, and subject-specific social media groups
- A comprehensive package of methodological resources
- A system of applied tasks and game-based, professionally-oriented scenarios
- Assessment tools for monitoring the development of students’ STEM competencies in mathematics education

To validate the efficacy of the structural and functional model of formation of STEM-competencies of students of professional pre-higher education institutions in mathematics teaching and its associated pedagogical conditions, a rigorous pedagogical experiment was conducted. Additionally, a diagnostic methodology was implemented to evaluate the effectiveness of the proposed tools.

The research spanned a four-year period (2019-2023) and was executed in four distinct phases:

1. Preparatory stage (2019-2020): This phase involved a theoretical examination of the need for STEM competency development among students in professional pre-higher education institutions, specifically in mathematics education.
2. Stating stage (2020-2021): The objective of this phase was to establish a baseline measurement of STEM competency levels among students at the outset of the experiment.
3. Formative stage
4. Control stage

Students of two groups of the specialty 072 “Finance, banking and insurance” of Separate structural unit ”Kryvyi Rih Professional College of State University of Economics and Technology” took part in the experimental study. The formative stage (2021-2022) was conducted with the aim of implementing the model and determining the level of formation of STEM-competencies of students of institutions of professional pre-higher education in teaching mathematics at the end of the experiment.

The control stage (2022-2023) provided the systematization of the results of the experiment, their statistical processing, analysis and formulation of conclusions.

To conduct the experiment, we formed a control group (40 students, CG) which was offered the traditional training and an experimental group (40 students, EG), which was taught with the introduction of the model implementation. After that, students were re-assessed with help of questionnaires, tests and control papers [13]. As a result we compared the levels of formation of individual components of students' STEM competencies in mathematics learning (value-motivational component; creative and active component; cognitive component; reflective-evaluative component) at the stating and formative stages of the experiment.

For example, let's check the reliability of the study results on the growth of the share of the sum of the sufficient and high levels of formation of the value-motivational component of students' STEM competencies at the beginning and end of the experimental study. The survey was conducted according to the questionnaire, which is presented in the manual Mathematics in STEM [13], summarized results regarding levels are presented in table 1.

Table 1. Value and motivational components of students' STEM competencies in Mathematics learning in the experimental and control groups.

The level	Before the experiment		After the experiment	
	experimental group	control group	experimental group	control group
Elementary	5 (12.5 %)	4 (10 %)	3 (7.5 %)	3 (7.5 %)
Intermediate	19 (47.5 %)	20 (50 %)	6 (15 %)	20 (50 %)
Sufficient	11 (27.5 %)	12 (30 %)	19 (47.5 %)	12 (30 %)
High	5 (12.5 %)	4 (10 %)	12 (30 %)	5 (12.5 %)
Total	40 (100 %)	40 (100 %)	40 (100 %)	40 (100 %)

We compared the shares before and after the experiment using the Fisher's angular transformation (table 2), for the value level $\alpha = 0.05$. At the stating stage of the experiment, it was established that the indicator of the sum of the sufficient and high levels of formation of the value-motivational component of the STEM-competencies of the CG students does not differ from the corresponding indicator of the EG. The significance level is 5 % the empirical value of the criterion at the end of the experiment is 3.286, which exceeds the critical value of 1.64. This means that the null hypothesis should be rejected: the indicator of the sum of the sufficient and high levels of formation of the value-motivational component of students' STEM competencies in mathematics learning in CG at the end of the experiment is significantly lower than the same indicator of EG at the end of the experiment.

Similar conclusions were drawn for other components of STEM competencies as well.

Table 2. Results of the study using Fisher's angular transformation for the value-motivational component formation.

Groups	Sufficient, high	Total	Share	Empirical, critical
CG Stating stage	16	40	0.4	ϕ empirical = 0
EG Stating stage	16	40	0.4	ϕ critical = 1.64
CG Formation stage	17	40	0.43	ϕ empirical =3.286
EG Formation stage	31	40	0.78	ϕ critical = 1.64

3. Conclusions

The implementation of the structural and functional model of formation of STEM-competencies of students of professional pre-higher education institutions in mathematics teaching, along with the associated pedagogical conditions, has yielded significant positive outcomes. The study demonstrates marked improvements across various dimensions of STEM competencies:

- Critical thinking skills
- Information and communication competence
- Project management and technological aptitude
- Core mathematical proficiency
- Fundamental competencies in natural sciences and technology

Statistical analysis of the experimental results reveals a consistent trend of positive changes aligned with the predefined criteria for STEM competency formation. Notably, a substantial proportion of students achieved sufficient and high levels of STEM competencies in mathematics.

The research substantiates that the integration of ICT in mathematics instruction, particularly in enhancing visualization and promoting research-oriented learning, significantly contributes to the development of STEM competencies among students in professional pre-higher education institutions.

The study establishes that effective STEM education implementation can be achieved through various strategies:

- Engaging students in independent research activities
- Integrating topics across different academic disciplines
- Implementing interdisciplinary projects
- Organizing scientific "picnics", themed days and weeks, and STEM festivals
- Facilitating holistic approaches to studying the world

The pedagogical experiment, conducted over four years (2019-2023), validated the effectiveness of the proposed model and methodologies. The study employed a rigorous four-stage approach: preparatory, stating, formative, and control stages, each contributing valuable insights to the research outcomes.

Future research directions could include:

- Developing methodological principles for incorporating immersive technologies in mathematics instruction
- Designing and implementing training programs for STEM educators in professional pre-higher education institutions
- Investigating long-term impacts of STEM competency development on students' career trajectories
- Exploring the potential of adaptive learning technologies in personalized STEM education

These areas represent promising avenues for further scientific inquiry, potentially leading to more advanced and tailored approaches to STEM education in professional pre-higher institutions.

Acknowledgments

This study is based on the doctoral research conducted by Olha S. Pylypenko under the supervision of Tetiana H. Kramarenko [2]. The research protocol was reviewed and approved by the ethics committee of Kryvyi Rih State Pedagogical University prior to the commencement of the study. All procedures performed in this study involving human participants were in accordance with the ethical standards of the Kryvyi Rih State Pedagogical University and with the 1964 Helsinki declaration and its later amendments.

Informed consent was obtained from all individual participants included in the study. Participants were informed about the purpose of the research, the voluntary nature of their participation, and their right to withdraw at any time without consequence. All data collected were anonymized to protect participant privacy. The researchers ensured that the study design and implementation adhered to the principles of beneficence, justice, and respect for persons throughout the research process.

The authors would like to express their sincere gratitude to the administration and faculty of the Separate structural unit "Kryvyi Rih Professional College of State University of Economics and Technology" for their support and cooperation throughout the research process. Special thanks are extended to the students who participated in this study, whose engagement and feedback were invaluable to the research outcomes.

We are grateful to our colleagues at the Department of Computer Science and Applied Mathematics at Kryvyi Rih State Pedagogical University for their insightful comments and constructive suggestions during the development of this research.

The authors also acknowledge the financial support provided by the Kryvyi Rih State Pedagogical University, which facilitated the implementation of STEM projects and the acquisition of necessary technological resources for this study.

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