3.2. Integration of Project-Based Learning and Digital Visualization for Developing Soft Skills of Future STEM Teachers

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***Abstract**. The article presents the theoretical and methodological foundations for developing the soft skills of future STEM teachers through a visual-digital approach. The relevance of the problem is justified by the ongoing digital transformation of education and the growing importance of interdisciplinary integration in teacher preparation. An analysis of Ukrainian and international research made it possible to identify the core soft skills critical thinking, communication, teamwork, creativity, and adaptability, and to determine their significance for the professional activity of STEM educators. The study of Ukrainian regulatory documents and international experience has confirmed the need for a coherent system of soft skills development within higher education.*

An original model of soft-skills development for future STEM teachers is proposed. It integrates four components: goal-oriented, content-based, procedural, and resultative, and unfolds through four consecutive stages: motivational-orientational, analytical-exploratory, constructive-activity, and reflective-evaluative. A distinctive feature of the model lies in the integration of visual-digital tools (Maple, GeoGebra, Blender, Tinkercad, PhET, mobile planetarium, and Go-Lab virtual laboratories) into interdisciplinary team tasks.

Pilot implementation of selected model components in the educational process of the Faculties of Natural-Mathematical and Engineering-Pedagogical Education demonstrated positive dynamics: the level of critical thinking (measured by an adapted Watson–Glaser test) increased by 12.4%, the average teamwork score rose from 3.62 to 4.28, and 78% of students reported higher motivation for collaboration. These results confirm the potential of the visual-digital approach for developing soft skills and substantiate the feasibility of its large-scale implementation.

***Keywords**: soft skills, STEM education, visual-digital approach, critical thinking, teamwork, future teachers, digital tools, interdisciplinary tasks, professional training, educational process.*

DOI: 10.31110/STEM-CaUk-3.2

Introduction

The contemporary preparation of future STEM teachers unfolds amid the rapid digital transformation of education, which necessitates the integration of advanced technologies, interdisciplinary approaches, and the development of soft skills as essential components of professional competence. The educational process should focus not only on mastering theoretical knowledge but also on cultivating the ability to work collaboratively, communicate effectively, think critically and creatively, and adapt to the dynamic conditions of professional activity.

Recent studies have demonstrated that project-based learning, built upon a visual-digital approach, serves as an effective means of achieving these goals (Semenikhina et al., 2021; Semenikhina et al., 2022b). Engaging students in the visualization of learning material, including through computer modeling, virtual laboratories, and digital design tools, enhances motivation, develops analytical and algorithmic thinking, and strengthens teamwork skills (Shyshenko et al., 2022; Yurchenko et al., 2025).

The relevance of this study is further supported by international and Ukrainian practices in implementing STEM education, which reveal the positive influence of integrated digital technologies on teacher preparation (Semenikhina et al., 2022a; Khvorostina et al., 2025). An analysis of global experience indicates a growing interest in employing STEM projects to foster problem-solving autonomy and the ability to generate innovative solutions (Chkana et al., 2025; Yurchenko et al., 2022).

Particular attention should be given to the role of digital and information culture, which serves as the foundation of effective professional performance for STEM educators. As shown in recent pedagogical research, developing digital culture and information hygiene improves the quality of work with digital resources and reduces the risks of misinformation (Drushlyak et al., 2025a; Rudenko et al., 2025; Yurchenko et al., 2024).

Therefore, the development of soft skills among future STEM teachers within a visual-digital approach emerges as a research and practical issue requiring a systematic and comprehensive investigation.

Project-based learning, as a pedagogical technology, is grounded in the active engagement of students in solving real, complex problems that require the integration of knowledge from multiple fields. Digital visualization, in turn, enables the creation of clear and interactive models that enhance the analytical, research, and communicative dimensions of project work. Both approaches possess a strong interdisciplinary potential and serve as effective tools for developing soft skills.

The relevance of this study is determined by several factors: the need to renew the content and methods of STEM teacher education with an emphasis on developing critical thinking and teamwork skills; the necessity of integrating modern digital technologies into the educational process not merely as illustrative materials but as instruments of active cognitive activity; and the insufficiently systematic implementation of project-based methods and digital visualization in Ukrainian higher education institutions.

The purpose of the study is to substantiate the effectiveness of integrating project-based learning and digital visualization for developing critical thinking and teamwork skills among future STEM teachers.

Research methods

To achieve the study's purpose and objectives, a set of interrelated methods was employed to provide theoretical substantiation, methodological design, and empirical verification of selected components of the model for developing soft skills among future STEM teachers, based on the visual-digital approach.

1. Theoretical methods

– Analysis of scholarly literature: both Ukrainian and international research on the formation of soft skills, STEM education development, and the integration of digital technologies into teacher training were examined. This analysis helped define the conceptual framework, identify key theoretical approaches, and reveal gaps in the methodological foundations for developing soft skills.

– Comparative-pedagogical analysis. The experiences of universities in Canada, Finland, Singapore, Poland, and Ukraine in applying visual-digital tools and project-oriented learning were analyzed to identify effective pedagogical practices that can be adapted for Ukrainian higher education.

– Modeling. A conceptual model for developing soft skills was designed, combining goal-oriented, content-based, procedural, and outcome-based components, implemented through four stages: motivational-orientational, analytical-exploratory, constructive-activity, and reflective-evaluative.

2. Empirical methods

– Pedagogical observation was conducted to document specific features of student interaction in teamwork, the use of visual-digital tools, and their influence on the dynamics of soft-skills development.

– Analysis of pilot-study results: indicators of students in experimental groups, where elements of the model (Maple, GeoGebra, Blender, Go-Lab, mobile planetarium) were implemented, were compared with those of control groups.

The use of these methods enabled a comprehensive examination of the theoretical foundations of soft-skills development among future STEM teachers, the design and substantiation of the author's model, and the collection of empirical data confirming the feasibility and promise of its integration into the higher education learning process.

Research Results

1. Theoretical Foundations of Project-Based Learning in STEM Education

1.1. Concept and Essence of Project-Based Learning

Project-Based Learning (PBL) is a pedagogical approach that organizes the educational process through students' engagement in complex, problem-oriented tasks that result in either a tangible product or a solution to a specific problem. Unlike traditional methods, which primarily focus on reproducing pre-existing knowledge, PBL encourages active involvement in research, analysis, synthesis of information, its practical application, and the presentation of outcomes (Driscoll, 2002; Thomas, 2000).

The core idea of PBL lies in the shift from passive knowledge acquisition to active knowledge construction through inquiry-based learning. This approach aligns with the principles of constructivism, which posits that knowledge is constructed through personal experience and social interaction (Schunk, 1999). As emphasized by John Dewey, learning should be structured so that students actively participate in solving real-world problems that carry personal and professional relevance, thereby acquiring experience applicable to future professional contexts (Dewey, 1963).

In competence-oriented education systems, PBL serves as an integrator of knowledge across disciplines and a catalyst for the development of soft skills such as critical thinking, communication, teamwork, and creativity (Piercey, 2010). For STEM education, this approach is particularly significant since solving problems that transcend a single subject area requires the use of interdisciplinary knowledge and effective collaboration within teams.

Research by J. Krajcik and P. Blumenfeld (2006) highlights that, in the STEM context, project-based learning facilitates a natural transition from theory to practice, fostering the development of scientific reasoning, experimental design, data processing, and presentation skills.

Thus, within the preparation of future STEM teachers, PBL functions not only as a teaching methodology but as a comprehensive pedagogical strategy that integrates disciplinary knowledge with the development of essential competencies required for effective professional performance in technologically advanced and dynamic educational environments.

1.2. Global and Ukrainian Experience

Project-based learning in STEM education is actively evolving worldwide; however, models of its implementation vary significantly depending on educational traditions, available resources, and national policies.

International experience demonstrates that in leading educational systems, such as those of the United States, Finland, Singapore, and Canada, PBL is an integrated element of curricula, spanning from primary school through higher education. For instance, Finland introduced the phenomenon-based learning model in 2016, which requires every student to complete at least one interdisciplinary project per year, combining various subjects into a single investigative theme (Lonka, 2018). In Singapore, university-based STEM centers organize collaborative projects involving students, faculty, and industry partners in fields such as robotics, biotechnology, and green technologies (Chong et al., 2018).

In the United States, the implementation of PBL in STEM education receives support at multiple levels, from federal initiatives such as the STEM Education Strategic Plan (2018) to local programs in individual school districts. According to Larmer, Mergendoller, and Boss (2015), successful STEM projects in the U.S. are characterized by their strong connection to real community issues and by the existence of robust systems for evaluating learning outcomes.

European experience also indicates a high level of integration of PBL into teacher education. In the United Kingdom, the National STEM Learning Centre (STEM Learning UK) coordinates a network of schools and universities that implement interdisciplinary projects with a focus on science, technology, engineering, and mathematics (STEM Learning, n.d.). In Spain and Italy, project-based learning is widely used in teacher professional development programs to build facilitation skills for managing student teamwork (Villanueva Baselga et al., 2022).

In Ukraine, the introduction of project-based learning in STEM education remains largely fragmented. According to the Concept for the Development of Natural and Mathematical Education (STEM Education) until 2027 (Cabinet of Ministers of

Ukraine, 2020), project activities are identified as one of the key methods for content integration, implemented through STEM courses, cases, laboratories, and engineering hackathons.

Recent Ukrainian studies reveal the potential of project-based learning for fostering both subject-specific and soft skills among future teachers. Implementing STEM projects that incorporate modeling and digital laboratory work enhances students' visualization skills (Semenikhina et al., 2021), advances digital and information culture (Yurchenko et al., 2024), and fosters competencies in creating maker-space learning environments (Shyshenko et al., 2022).

At the same time, as noted by O. Semenikhina et al. (2022b), the adoption of project-based methods remains inconsistent, largely depending on the initiative of individual instructors and often occurring outside the formal curriculum. Other researchers emphasize that even within individual disciplines, project-based activities can be effectively combined with visual and digital technologies to stimulate critical thinking and teamwork (Semenikhina et al., 2022a; Yurchenko et al., 2025).

Positive examples in Ukraine include the operation of mobile scientific and educational spaces (mobile planetariums, STEM laboratories), participation of schools in international initiatives such as eTwinning and Erasmus+, regional competitions in technical creativity, and local projects focused on developing integrated STEM tasks (Drushlyak et al., 2025b; Rudenko et al., 2022; Khvorostina et al., 2025).

The absence of national methodological guidelines for organizing interdisciplinary projects and the limited availability of technical infrastructure remain key barriers to large-scale implementation of this approach in teacher education. Thus, while international practice demonstrates stable, well-supported models of PBL in STEM, Ukraine still faces the challenge of developing unified methodological tools and a sufficient resource base to ensure the systematic integration of project-based learning into pedagogical education.

1.3. Pedagogical Opportunities for Developing Soft Skills

Project-based learning in STEM education is among the most effective tools for developing soft skills, as it combines meaningful, interdisciplinary activities with intensive communication, collaboration, and the practical application of knowledge. According to the Partnership for 21st Century Learning (2019), critical thinking, creativity, communication, and teamwork are best cultivated in environments where learning is centered on solving authentic problems rather than reproducing pre-existing knowledge (P21 Framework).

The development of critical thinking in PBL occurs through analyzing problem situations, formulating hypotheses, searching for and evaluating information, and verifying the soundness of conclusions. As noted by N. Habrusieva and N. Shostakivska (2014), critical thinking in an educational setting involves cognitive skills of interpretation, analysis, evaluation, and both inductive and deductive reasoning (Critical Thinking: What It Is and Why It Counts). In STEM projects, these skills are naturally practiced in the context of interdisciplinary inquiry, particularly through process modeling and digital data analysis (Semenikhina et al., 2022a).

Teamwork is a fundamental component of PBL, as most projects require collaborative task execution with role distribution, collective planning, and mutual accountability. According to B. Tuckman’s group development model (1965), effective teams progress through stages of forming, storming, norming, and performing. In STEM projects, this process often accelerates due to the need for rapid joint decision-making and adaptability to changing project conditions, especially when tasks involve creating digital prototypes or using interactive visualizations (Yurchenko et al., 2025).

Creativity is fostered by the necessity to generate unconventional solutions and design original models, visualizations, or prototypes. V. Holskyi et al. (2025) emphasize that project-based learning creates a space of “guided freedom,” where students can experiment within clearly defined problem boundaries. This approach is effectively implemented in Ukrainian practice, where students design mathematical models or interactive maker-space environments using tools such as GeoGebra (Shyshenko et al., 2022) or complex digital laboratories.

Communication skills are developed both within the team and during project presentations to external audiences. These include verbal, written, and visual communication, as well as the use of digital tools for remote collaboration (Google Workspace, Miro, Trello). Research by Binkley et al. (2012) within the Assessment and Teaching of 21st Century Skills project confirms that the effective use of technology in group work significantly enhances participants' communicative potential. Ukrainian scholars also emphasize the importance of integrating communication and digital-information culture within project-based learning (Yurchenko et al., 2024).

Thus, project-based learning in the STEM context demonstrates considerable pedagogical potential for developing core competencies in critical thinking, teamwork, creativity, and communication that determine future teachers' readiness for effective professional activity in dynamic and technologically rich environments. The greatest impact is achieved when project work is supported by digital visualization tools that strengthen collaborative data analysis, reasoning, and the presentation of results.

Conclusions to Research Results 1

The theoretical analysis of scientific literature and regulatory documents in the field of higher pedagogical education has demonstrated the growing importance of soft-skills development in the preparation of future STEM teachers. In the current era of digital transformation in education, both in Ukraine and globally, the development of soft skills has become a strategic direction that complements professional knowledge and ensures the readiness of future educators to work in environments characterized by interdisciplinary integration and rapid technological change.

An examination of Ukrainian and international studies (Binkley et al., 2012; Fullan & Langworthy, 2014; Trilling & Fadel, 2009) revealed that soft skills, such as critical thinking, communication, creativity, teamwork, and adaptability, are regarded as core components of teachers' professional competence. At the same time, it was found that in most educational programs, the development of these skills is either not integrated into the content of academic disciplines or implemented sporadically, without a coherent methodological foundation.

The analysis of legal and policy frameworks confirmed that the concept of the "educational process," as defined in the Law of Ukraine on Education, presupposes the formation of both professional and general competencies, including soft skills. This aligns with contemporary requirements for teacher training. However, existing documents lack specific methodological guidelines on the use of digital visualization as a tool for developing soft skills, which creates a gap between normative intentions and practical implementation.

Therefore, the findings confirm the need to establish a comprehensive theoretical and methodological system for developing soft skills in future STEM teachers, one that is integrated into the educational process and designed with regard to modern digital capabilities, particularly the visual-digital approach. This conclusion provides the foundation for the conceptual framework presented in the following sections.

2. Digital Visualization as a Tool for Supporting Project-Based Learning

2.1. Concept and Types of Digital Visualization

In contemporary STEM education, digital visualization is understood as the integration of computer technologies to represent data, models, or concepts in graphical, three-dimensional, or interactive forms. It serves not only as a technical instrument but also as a pedagogical tool that transforms how knowledge is presented and internalized. According to C. Ware, visualization is the process of transforming abstract data into a form interpretable through the human visual system, thereby enhancing understanding and supporting decision-making (Ware, 2012).

Within the framework of STEM disciplines, digital visualization encompasses a wide range of methods from creating simple static charts to designing fully interactive and immersive environments. R. Mayer, in his Cognitive Theory of Multimedia Learning, demonstrated that combining visual and verbal learning channels (the multimedia principle) significantly increases the effectiveness of comprehension and retention compared to using a single channel (Mayer, 2009). This principle is particularly relevant in STEM education, where many concepts, such as molecular interactions, complex mathematical functions, and engineering structures, are highly abstract and require visual representation for deeper understanding.

Studies by A. Stull and R. Mayer (2007) confirm that the use of graphical images and visual models promotes the development of analytical, comparative, and generalization skills, as it simultaneously activates both verbal-logical and spatial-visual processing channels. Consequently, students not only achieve a better understanding of learning material but also demonstrate an enhanced ability to apply knowledge in new situations, which is essential for project-based learning.

From a functional perspective, several major types of digital visualization can be identified in STEM education:

Illustrative visualization involves presenting information in the form of static images, diagrams, charts, or infographics. It enables quick perception of overall structure or relationships, for instance, a function graph or an electrical circuit diagram. As shown by Bateman et al. (2010), infographics enhance student engagement and facilitate the retention of factual information in memory.

Modeling visualization refers to the creation of 2D and 3D models of objects, systems, or processes that allow learners to explore their properties under variable conditions. Examples include a 3D model of a crystal lattice in chemistry or an engineering prototype of a structural design. The use of modeling in education contributes to the development of spatial reasoning and the ability to work with abstract concepts (Landeschi, 2023).

Simulation-based visualization offers an interactive, real-time representation of system behavior, allowing users to adjust parameters and observe the resulting effects. For example, PhET Interactive Simulations can be used to study Newton’s laws or chemical equilibrium, allowing students to test hypotheses without the risks and costs associated with real-world experiments (Kudria et al., 2020).

Immersive visualization employs virtual reality (VR) and augmented reality (AR) technologies to create environments that produce a sense of full presence. Research by Radianti et al. (2020) demonstrates that VR/AR-based approaches foster research and communication skills while also increasing student motivation in STEM learning.

The application of all these visualization formats in project-based learning creates conditions for:

• deeper understanding of complex phenomena by allowing observation of their dynamic changes;

• development of data analysis and predictive reasoning based on visual information;

• formation of research-oriented behavior as students experiment with model parameters and test hypotheses;

• enhancement of teamwork through collaborative interaction with visual objects in a digital environment.

Thus, digital visualization in STEM not only supports knowledge acquisition but also serves as a vital factor in developing soft skills, particularly within project-based learning, where visual tools become a shared space for discussion, analysis, and decision-making.

2.2. Specialized Software in STEM Education

Effective implementation of digital visualization in project-based learning requires tools that enable model creation and analysis, numerical computation, animation, and interactive data presentation. The choice of software depends on the project's objectives, students' level of preparation, and the availability of institutional resources. Below are examples of widely used tools that support project-based learning and the development of soft skills in STEM education.

GeoGebra. GeoGebra is a free dynamic mathematics software that integrates algebra, geometry, spreadsheets, graphing, statistics, and 3D modeling. One of its major advantages lies in its ability to work simultaneously with both analytical and visual representations of an object, thereby promoting a better understanding of the relationship between formulas and graphical models. According to V. Pikalova (2020), GeoGebra provides an interactive environment suitable for both individual and group research. Its use in STEM projects enables the creation of visual scenarios that can be embedded into online resources or presented during project defense.

WolframAlpha. Wolfram Alpha is a computational intelligence service capable of performing automated calculations, generating graphs, and producing visualizations based on user input. For STEM students, this tool serves not only as a calculator but also as a platform for generating ideas and analyzing data. As noted by Wolfram Research (2023), Wolfram Alpha supports a wide range of disciplines, including mathematical analysis, statistics, chemistry, and astronomy (https://www.wolframalpha.com). In collaborative projects, it allows teams to quickly test hypotheses and optimize model parameters, which is particularly important in projects with strict time constraints.

Maple. Maple is a powerful computer algebra system that combines analytical computation, symbolic mathematics, and advanced visualization capabilities. In STEM projects, Maple is used to solve complex mathematical problems, simulate physical processes, analyze experimental data, and construct interactive graphs. Its ability to generate animated 2D and 3D visualizations makes it an effective tool for explaining system dynamics, demonstrating dependencies, and conducting virtual experiments. T. Shifrin (2012) demonstrated that the use of Maple in higher mathematics education enhances students' analytical and critical thinking skills, while mastery of the software is essential for teachers of natural sciences (Semenikhina, 2014). Research by Shyshenko et al. (2023) further confirms the pedagogical relevance of facilitating mathematics learning through Maple-based instruction.

PhET Interactive Simulations. PhET is a collection of interactive simulations developed by the University of Colorado, covering physics, chemistry, biology, mathematics, and other

STEM domains. These simulations model real-world systems in a user-friendly interface, allowing parameter manipulation and real-time observation of outcomes. According to A. Yurchenko et al. (2023) found that PhET increases student engagement and promotes a deeper understanding of scientific principles by offering interactive experimentation without the risks and costs associated with physical laboratories.

Tinkercad. Tinkercad is a free web-based platform by Autodesk for 3D modeling, electronic circuit design, and microcontroller programming. Its intuitive interface makes it accessible for beginners, while its functionality is sufficient for prototype development in educational projects. According to Autodesk (2023), Tinkercad is widely used in school and university STEM courses for creating quick models that can later be 3D printed or integrated into virtual simulations (Kramar & Shyshkina, 2024).

Blender. Blender is an open-source software for creating advanced 3D models, animations, and visual effects. Its flexibility allows it to be applied in a wide variety of STEM projects, ranging from architectural visualization to physical process modeling. The community-driven nature of Blender provides free access to tools that would otherwise be costly in commercial alternatives (https://www.blender.org), making it particularly valuable for educational institutions with limited budgets.

Go-Lab. Go-Lab is a European online platform designed to organize virtual laboratories and integrate experimental activities into the learning process. It enables the creation of customized learning scenarios that combine simulations, instructional materials, and data analysis tools. As noted by de Jong et al. (2014) and V. Vember (2018), using Go-Lab in STEM education enhances learning efficiency by linking theoretical content with research-based activity and the digital visualization of results.

Digital laboratories. Digital laboratories are mobile or stationary complexes equipped with specialized software and devices for conducting interactive experiments. A prominent example is the mobile planetarium, which allows visualization of astronomical phenomena, exploration of the universe's structure, and simulation of celestial motion through full-dome projection.

As G. DeBoer et al. (2014) point out, immersive technologies, including digital planetariums, significantly increase motivation and improve comprehension of complex astronomical concepts among students.

Overall, these tools form a technological ecosystem that enriches project-based learning in STEM education. They promote not only the visualization of abstract ideas but also collaborative problem-solving, analytical reasoning, and creativity – essential elements in the development of soft skills among future STEM teachers.

Mobile laboratories may also include portable kits for conducting physical, chemical, or biological experiments, where the results are instantly displayed as digital graphs, tables, and models. This format is particularly effective in project-based learning because it enables research activities to be conducted in any educational setting, even without access to a stationary laboratory. Moreover, it fosters the development of soft skills through collaborative interaction and collective discussion of experimental outcomes.

Thus, specialized software serves as a central component of digital visualization in STEM projects. It allows students not only to observe the final results of their ideas but also to continuously interact with models, modifying them according to new data and changing conditions. When combined with project-based learning, these tools create an environment that actively cultivates critical thinking, teamwork, and creativity, the soft skills that are essential for preparing future STEM teachers.

2.3. Pedagogical Potential of Digital Visualization

Digital visualization in project-based learning serves a dual function: on the one hand, it acts as a tool for explaining and exploring complex phenomena; on the other, it serves as a medium for active student interaction, directly contributing to the development of soft skills.

Critical thinking develops through the ability to analyze and interpret visual data, test alternative scenarios, and modify models in real time. O. Lysievych et al. (2025) demonstrate that integrating digital models into group discussions strengthens argumentation and fosters a deeper understanding of scientific concepts. When students work with tools such as Maple or GeoGebra, they do not simply construct graphs or 3D models; they also critically assess the accuracy of calculations, the adequacy of models, and potential sources of error.

Teamwork in a digital environment involves collaborative planning, role distribution, and coordination during the creation and analysis of visual materials. In projects that utilize Blender or Tinkercad, for example, some participants may focus on 3D modeling, others on data analysis using Maple, and others on preparing visual presentations of the results. Such division of labor encourages the development of complementary competencies and effective communication skills, which, according to B. Tuckman (1965), are essential for a team to reach the stage of productive collaboration.

Communication skills are cultivated not only through verbal discussions but also through the creation of explanatory animations, infographics, and interactive presentations. The use of mobile digital laboratories, such as the mobile planetarium, enables students to present scientific phenomena to a wider audience, explaining them in an accessible language. G. DeBoer et al. (2014) emphasize that such interactive formats enhance not only scientific literacy but also the ability to adjust communication style to the audience's level of understanding.

Creativity in digital visualization is stimulated by the opportunity to experiment with both the form and mode of presenting material. Tools like PhET Interactive Simulations and Go-Lab allow the creation of unique research scenarios that integrate animation, interactivity, and adaptable modeling. D. Piercey (2010) notes that such a "guided inquiry environment" provides space for creative expression while maintaining a structured focus on achieving educational goals.

Through the integration of project-based learning and digital visualization, students also develop organizational and leadership competencies. Complex STEM projects often require coordination across multiple work streams: computation, visualization, modeling, and presentation. This compels students to structure workflows, set priorities, and monitor deadlines, all of which are essential components of twenty-first-century skills (Binkley et al., 2012).

Thus, digital visualization in project-based learning within STEM disciplines creates unique conditions for the comprehensive development of soft skills. It not only deepens understanding of learning material but also provides an interactive environment for collaboration, collective decision-making, and creative problem-solving.

Conclusions to Research Results 2

The study of pedagogical experience and contemporary methodological approaches to training future STEM teachers made it possible to identify the key concepts underlying the design of a model for developing soft skills through a visual-digital approach. The analysis of Ukrainian and international practices demonstrated that the most effective educational models for fostering soft skills are those that integrate teamwork, problem-based tasks, and digital tools for modeling and visualization.

An examination of the practices of universities in Canada, Finland, Singapore, and Poland revealed that the systematic use of visual-digital technologies such as virtual laboratories, 3D modeling, and simulation environments not only enhances mastery of subject-specific knowledge but also promotes the development of critical thinking, communication, and creativity among students. In Ukrainian higher education, certain elements of these approaches are implemented through STEM projects; however, there is still no comprehensive methodological framework adapted specifically to teacher preparation.

The analysis showed that combining the visual-digital approach with the principles of interdisciplinarity and project-based learning creates favorable conditions for developing soft skills in the natural process of mastering professional knowledge. The use of tools such as Maple, GeoGebra, Blender, Tinkercad, PhET, and the mobile planetarium enables the design of complex tasks that require students to apply technical, communicative, and creative abilities simultaneously.

Thus, the analysis of pedagogical practices and methodological approaches substantiates the feasibility of developing an original model that integrates the development of soft skills with the study of STEM disciplines by incorporating digital visualization into the educational process. This conclusion provided the foundation for the detailed design of the model presented in the subsequent sections.

3. Development of Critical Thinking and Teamwork among Future STEM Teachers through the Integration of Project-Based Learning and Digital Visualization

3.1. Theoretical approaches to the definition of critical thinking

In contemporary pedagogy, critical thinking is defined as the ability to consciously, reflectively, and logically analyze information, construct arguments, and make well-reasoned decisions (Usanova et al., 2024). In the context of preparing future STEM teachers, this competence is particularly important, as it relates not only to understanding subject-specific content but also to the capacity to evaluate scientific data, critically assess information sources, and adapt teaching methods to specific learning situations.

According to R. Ennis’s model, critical thinking encompasses five key components: identifying a problem, seeking information, evaluating sources, constructing arguments, and drawing conclusions (Ennis, 2018). In STEM education, these stages are naturally embedded in project-based learning, where students work on open-ended problems that lack a single correct solution and require a thoughtful choice of methods and approaches.

Digital visualization tools play a crucial role in developing critical thinking. Research by Zhang and Linn (2011) demonstrates that interactive models enhance comprehension of complex phenomena and foster the ability to formulate and test hypotheses. For instance, using Maple to construct graphical representations of differential equations enables students to visually assess changes in system behavior under varying parameters and to critically analyze which conditions lead to stable or unstable outcomes.

Moreover, critical thinking in STEM fields has a pronounced interdisciplinary dimension. As D. Willingham (2008) argues, students develop this competence most effectively when tasks integrate multiple subject areas and require applying knowledge in new contexts. In this regard, project-based learning enhanced by digital visualization creates a "data-rich environment" in which students not only receive information but also actively work with it, pose analytical questions, and draw evidence-based conclusions.

An essential condition for effectively developing critical thinking is structuring the learning process so that students move beyond content reproduction toward active engagement in discussions, analysis of alternative solutions, and comparison of different models. To achieve this, it is advisable to employ interactive, dialogue-oriented methods, including:

Case study based on visualized data. The case study method in STEM education becomes particularly effective when combined with digital visualization. This approach allows students not only to analyze a problem described textually but also to interact with its graphical or interactive representation. For example, while studying an engineering problem related to energy optimization, students may work with a digital model of a building created in Blender or Tinkercad and examine related data displayed as interactive Maple charts. Learners analyze both visual and numerical indicators, identify inefficiencies, propose solutions, and justify their decisions. Such an approach activates all stages of critical thinking described in R. Ennis's model (2018), as it requires evaluating sources, testing hypotheses, and formulating conclusions based on visually supported evidence.

Situational modeling in digital laboratories. Situational modeling involves creating conditions that closely simulate real-world environments, allowing students to investigate various processes and phenomena. Digital laboratories, such as Go-Lab and PhET Interactive Simulations, enable the reproduction of physical, chemical, or biological processes, allowing users to manipulate model parameters and observe outcomes in real-time. For instance, in PhET, students can simulate the movement of electrons in a conductor by adjusting voltage and resistance, while Go-Lab allows the creation of integrated learning scenarios that combine multiple simulations and data analysis modules. Under these conditions, students learn to critically evaluate causal relationships, test predictions, and identify optimal problem-solving strategies. Research by de Jong et al. (2014) shows that such environments significantly enhance analytical activity by enabling immediate verification of results.

Digitally supported debates. The debate method develops argumentation and counterargumentation skills, which form the core of critical thinking. In this format, digital visualization serves as a basis for evidence-based reasoning. Students prepare presentations incorporating results from Maple (analytical computations and graphs), GeoGebra (dynamic mathematical models), or Blender (3D representations of objects or processes). During the debates, each team presents its conclusions supported by visual evidence and poses clarifying questions to opponents, referring to visual proofs. This activity helps students develop their ability to evaluate the logical coherence of arguments, identify reasoning errors, and adjust their stance in response to compelling evidence. As noted by D. Piercey (2010), integrating visual evidence into communicative formats substantially improves both the quality of discourse and the depth of problem comprehension.

Thus, critical thinking in STEM education develops most effectively within an integrated environment that combines project-based learning with digital visualization tools. This integration not only deepens understanding of subject content but also strengthens the ability to make well-reasoned, evidence-based decisions, an essential competence for future educators in scientific and technological domains.

3.2. Mechanisms of teamwork formation in STEM projects using digital visualization

Teamwork in STEM education is not limited to completing tasks collaboratively; it represents a complex set of interrelated processes that involve coordinating actions, assigning roles, maintaining effective communication, and providing mutual support in pursuit of a shared goal. According to B. Tuckman's (1965) model of group development, teams progress through four stages: forming, storming, norming, and performing. Each of these stages can be strengthened through the use of digital visualization tools.

In STEM projects, digital visualization serves as a shared, interactive space where all team members can simultaneously view and modify project outputs, significantly reducing the risk of misunderstanding and enhancing collaborative productivity. Research by Johnson and Johnson (2017) emphasizes that working jointly on visual models increases team interdependence and fosters trust, a factor that is crucial for effective cooperation.

Key mechanisms of teamwork formation through digital visualization

Role distribution based on competencies and interests.

Digital projects that incorporate visualization enable the formation of teams with clearly defined functional roles. For example, in a collaborative project on ecosystem modeling:

- one student is responsible for creating the 3D model in Blender;
- another handles mathematical analysis in Maple;
- a third prepares an interactive presentation using GeoGebra or Tinkercad.

This approach not only takes into account individual strengths but also encourages peer learning, as participants must integrate their outputs into a unified final product.

Use of virtual environments for collaborative editing.

Cloud-based platforms and shared workspaces, such as Go-Lab or online versions of Tinkercad, enable students to edit models synchronously, leave comments, and track changes in real time. This minimizes communication delays and facilitates consensus-building, especially in remote or blended learning settings. Research by Crawford and Wang (2016) demonstrates that collaboration within visually rich environments fosters a sense of collective responsibility for outcomes.

Visualization of progress and task management.

Integrating digital visualization into project management systems (e.g., Trello, Miro, Notion) enables teams to monitor the overall workflow, track completed stages, and identify potential delays. In a STEM context, this may include an interactive Gantt chart in which each task is linked to a specific visual model or simulation. Such tools help students develop planning, prioritization, and collective quality control skills.

Using visualization for collaborative problem-solving.

When a team encounters a technical or conceptual challenge, digital visualization enables the rapid creation of multiple alternative solutions and facilitates visual discussion. For example, when working with a mobile planetarium, students can visualize different celestial motion scenarios and collectively select the optimal one for demonstration. This process strengthens collective reasoning and cognitive flexibility, which are hallmarks of high-performing teams (Moskalenko, 2023).

Reflection through visual outcomes.

After project completion, visual outputs, such as graphs, diagrams, 3D models, and animations, serve as material for joint analysis and self-assessment. This allows the team to identify which interaction strategies were effective and which require improvement. Such reflective practice fosters metacognitive awareness and cultivates a culture of continuous enhancement.

Thus, digital visualization not only enhances the educational dimension of teamwork in STEM projects but also fosters the development of essential soft skills, including coordination, effective communication, leadership, mutual support, and shared decision-making. Integrating visualization tools across all stages of team activity, from planning to presenting results, transforms the learning process into a dynamic form of collaboration that closely mirrors real professional practices in science and technology fields.

3.3. An integrated approach to the development of critical thinking and teamwork in STEM projects using digital visualization

The development of critical thinking and teamwork among future STEM teachers should not be viewed as two isolated processes. In contemporary pedagogy, an integrated approach is gaining traction, one that emphasizes the mutual reinforcement of these competencies through collaborative learning, particularly within project-based learning environments enhanced by digital visualization. According to J. Kolodner et al. (2003), combining analytical and social dimensions of learning helps create “learning communities of inquiry,” where participants not only master subject-specific knowledge but also develop social and cognitive skills through collective problem-solving.

Within such an integrated environment, digital visualization performs at least three essential functions:

A shared tool for analysis and decision-making. Interactive visual models (created in Maple, GeoGebra, Blender, or Tinkercad) function as a “zone of collective insight,” allowing all team members to simultaneously analyze data, test hypotheses, and propose alternatives. For instance, in a project on optimizing urban infrastructure, a group of students may build a 3D model of a street that reflects traffic patterns and use it to discuss potential redesigns, evaluating the implications of each option. This activity simultaneously requires analytical flexibility, a component of critical thinking, and coordinated decision-making, both of which are essential components of teamwork.

Structuring team interaction through analytical stages. The integration of the two competencies is most effective when teamwork is organized in a way that requires each stage of collaboration to incorporate elements of critical thinking. According to D. Johnson and F. Johnson’s (2017) cooperative learning model, effective group work includes problem formulation, information search and analysis, argument construction, solution evaluation, and synthesis. Incorporating digital visualization into each of these stages, from initial schematic design to the final 3D presentation, not only supports cognitive processing but also ensures transparency and shared understanding among team members.

Cultivating a culture of reasoned collaboration. The integrated approach presupposes that all team members actively contribute to the creation and defense of solutions. Visualization strengthens argumentation by making reasoning visible: rather than relying on abstract verbal explanations, participants can present concrete visual models, graphs, or simulations that substantiate their claims. Studies by Moskalenko (2015) demonstrate that collective discussion of visualized results enhances critical analysis and fosters consensus-oriented decision-making.

Practical implementation of this integrated approach in the preparation of future STEM teachers may include:

• Interdisciplinary projects where technical, mathematical, and pedagogical components are addressed collaboratively, using visual tools for analysis and decision-making.

• Hybrid learning formats that combine synchronous teamwork in virtual environments with asynchronous analytical processing of data.

• Reflective sessions in which teams review their visual materials, evaluate interaction effectiveness, and identify directions for improving both technical and communication skills.

Thus, the integrated approach transforms the development of critical thinking and teamwork from parallel processes into interdependent elements of a unified educational framework. Within this model, digital visualization serves as the connecting link that unites analytical and social dimensions of learning, equipping future STEM teachers with the tools necessary for effective performance in today’s scientific and technological environment.

Conclusions to Research Results 3

The analysis of theoretical foundations and practical mechanisms for developing critical thinking and teamwork among future STEM teachers demonstrates that integrating project-based learning with digital visualization creates unique conditions for cultivating these essential soft skills. Critical thinking in the STEM context is conceptualized as the ability to analyze complex systems, test hypotheses, evaluate the validity of data, and draw reasoned conclusions based on visually verified evidence. The use of digital tools, such as mathematical software like Maple and GeoGebra, and 3D modeling platforms like Blender and Tinkercad, provides students with access to dynamic, interactive representations that deepen analytical engagement and facilitate the assimilation of interdisciplinary knowledge.

Teamwork in STEM projects involving digital visualization is understood as a coordinated process of role distribution, joint problem-solving, and goal achievement through ongoing communication and the exchange of visualized outcomes. The use of virtual environments for collaborative model editing, visual progress tracking in project management systems, and collective problem-solving increases team interdependence, fosters a culture of trust and mutual support, and enables the development of effective leadership.

An integrated approach to developing critical thinking and teamwork implies their mutual reinforcement through the design of learning scenarios where each stage of collaboration includes an analytical component, and each analytical decision emerges through collective discussion. Within this framework, digital visualization functions as a shared tool for analysis, argumentation, and decision-making, ensuring transparency and accessibility of information for all participants.

Thus, combining project-based learning with digital visualization in the preparation of future STEM teachers enables the simultaneous development of critical thinking and teamwork as interconnected elements of professional competence. This integration enhances students' readiness to operate in high-tech, dynamic, and interdisciplinary environments, aligning with contemporary requirements for teacher education in STEM fields.

4. Integration of project-based learning and digital visualization

4.1. Methodological model of soft skills development of future teachers of STEM disciplines on the basis of a visual and digital approach

The proposed methodological model for developing soft skills in future STEM teachers through a visual-digital approach (Figure 1) is based on the idea of integrating modern digital visualization tools into the educational process to comprehensively foster key soft skills critical thinking, teamwork, communication abilities, creativity, digital literacy, and self-regulation.

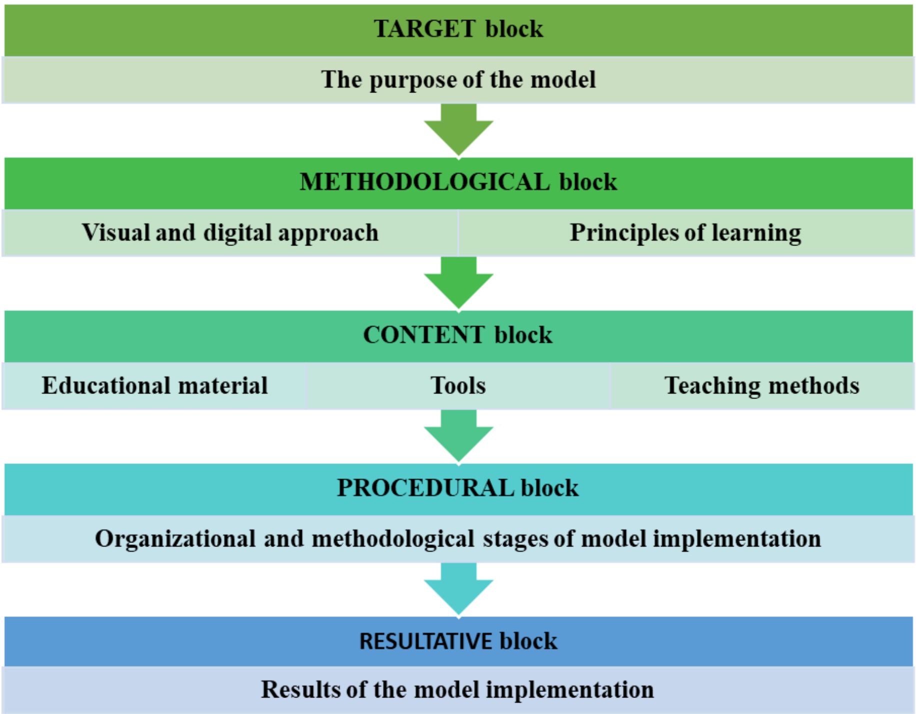

Figure 1. Structural blocks of the model

Target Block.

The goal of the model is to ensure the purposeful and guided development of soft skills in future STEM teachers through the application of a visual-digital approach within project-based and research-oriented learning.

Methodological Block.

The implementation of the model is grounded in the visual-digital approach and a set of core principles: adaptability (flexible adjustment of content, methods, and forms of work depending on students' preparedness and institutional resources); graduality (progressive introduction of model elements from individual visualization-based tasks to full-scale team STEM projects); interdisciplinarity (integration of knowledge and skills from various STEM fields within a single task or project); integration of soft skills into professional training (developing critical thinking, teamwork, and other soft skills through solving subject-specific problems); visual-digital integration (mandatory inclusion of digital visualization at all stages of work); team interaction (structured role distribution within projects, promoting interdependence among participants); and reflectivity (continuous student engagement in analyzing both the process and outcomes of their work).

Content Block.

This block defines the educational material, tools, and methods used within the model. It integrates interdisciplinary STEM tasks that require collaborative problem-solving supported by digital visualization tools such as Maple, GeoGebra, Tinkercad, Blender, mobile planetariums, Go-Lab, and PhET. It also ensures the combination of academic and applied content through problem-based cases, providing flexible adaptation options for students with different proficiency levels.

Procedural Block.

This block outlines the organizational and methodological stages of implementing the model:

• Motivational–orientation stage introducing students to the problem through visually represented contexts (e.g., interactive infographics, simulations);

• Analytical–exploratory stage working with visual models to collect and analyze data, formulate hypotheses, and search for solutions;

• Constructive–activity stage creating original digital visualizations and collaboratively processing results;

• Reflective–evaluative stage group discussions, project defense, self- and peer-assessment of soft skill development.

Resultative Block.

Expected outcomes include:

• an increased level of key soft skills (assessed via developed diagnostic criteria);

• enhanced ability to integrate digital visualization tools into future pedagogical practice;

• readiness to work in interdisciplinary teams within digital learning environments.

Verification of results is carried out using diagnostic tools (questionnaires, observations, analysis of student products, self-assessment) adapted to visual-digital task formats.

The model is conceptually based on project-based learning (Thomas, 2000), collaborative learning (Johnson & Johnson, 2017), and visual learning (Mayer, 2009), which together create a learning environment conducive to the synchronous development of cognitive and social competencies. As shown by Z. Zhang and M. Linn (2011), digital visualization significantly enhances the quality of reasoning and students' engagement in discussions, directly correlating with the development of critical thinking and teamwork.

4.2. Pedagogical conditions for effective implementation of the model

The effectiveness of the proposed model for developing soft skills in future STEM teachers through a visual-digital approach largely depends on creating a set of pedagogical conditions that ensure the interconnected functioning of cognitive, communicative, and technical-technological components of learning. Based on an analysis of contemporary research in STEM education (Binkley et al., 2012; Johnson & Johnson, 2017; Mayer, 2009), the following key conditions were identified:

Condition 1. Integration of digital visualization tools into problem-based learning tasks.

Soft skills develop most effectively when digital visualization tools function not as supplementary aids but as integral components of problem-solving. In projects that utilize Maple or GeoGebra, mathematical computations are combined with the construction of visual models, which later become the foundation for group discussions and evidence-based decision-making. As noted by Z. Zhang and M. Linn (2011), linking digital modeling with discussion deepens analytical reasoning and strengthens students' ability to defend their positions.

Example of implementation: when studying physical processes, students use Go-Lab to simulate an experiment and then work in teams to analyze how changing parameters affect outcomes, interpreting the results through visual graphs and animations.

Condition 2. Organization of team interaction with clearly defined roles.

The development of teamwork, communication, and responsibility requires an organized learning environment in which each participant assumes a distinct role linked to digital visualization. For instance, one student may design a 3D model in Blender, another process data in Maple, and a third prepare an interactive presentation in Tinkercad or a mobile planetarium environment. According to Johnson and Johnson (2017), such role differentiation enhances interdependence, boosts motivation, and fosters a sense of collective accountability.

Example of implementation: in a mathematics teaching methods course, a student team creates visualizations of geometry problems. Some participants build dynamic models in GeoGebra, while others produce video explanations or animated walkthroughs.

Condition 3. Use of reflective and analytical practices based on visual materials.

Reflection is essential for the development of soft skills because it enables students to evaluate both learning outcomes and teamwork processes. Visual materials such as graphs, diagrams, animations, and 3D models provide a foundation for collective analysis, strengthening argumentation and promoting critical thinking. O. Moskalenko (2023) shows that group discussions of visualized results help identify errors and generate more effective solutions.

Example of implementation: after completing a project, the team holds a reflection session where all visual materials are compiled in a shared online workspace (e.g., Miro or Notion), allowing each participant to comment on the strengths and weaknesses of the group's collaboration.

Condition 4. Provision of access to modern digital infrastructure and learning resources.

Implementing the visual-digital approach is impossible without adequate technical support. This includes access to licensed software (Maple, Blender, Tinkercad), online platforms (Go-Lab, PhET), equipment for mobile laboratories (including mobile planetariums), and reliable internet connectivity. According to R. Mayer (2009), the availability of visualization tools is a crucial factor in the effective acquisition of knowledge and the development of cognitive skills.

Example of implementation: a university establishes a “digital STEM lab” where students engage with VR-based physics experiments and participate in interdisciplinary collaborative projects.

In summary, the successful implementation of the model requires a holistic combination of methodological, organizational, and technological measures aimed at integrating digital visualization into the learning process. Compliance with these pedagogical conditions not only enhances the development of soft skills but also equips future STEM teachers with the readiness to operate professionally in the context of the ongoing digital transformation of education.

4.3. Stages of Implementing the Model in the Educational Process

The implementation of the model for developing soft skills in future STEM teachers through a visual-digital approach requires a phased organization of the educational process that ensures the logical sequencing of competence formation. Based on the analysis of modern pedagogical frameworks (Thomas, 2000; Johnson & Johnson, 2017; Mayer, 2009), four interrelated stages have been identified.

1. Motivational–Orientation Stage

Objective: to foster students’ intrinsic motivation and engagement in developing soft skills through STEM projects supported by digital visualization.

Instructor's actions: introduce current challenges and problems in STEM fields through visual materials such as infographics, 3D animations, or virtual tours of laboratories.

Role of digital visualization: to create emotional engagement and demonstrate the practical relevance of learning tasks.

Examples of tools: mobile planetarium (for visualizing astronomical phenomena), PhET interactive simulations, and video analyses of engineering projects developed in Blender.

2. Analytical–Exploratory Stage

Objective: to develop students' ability to critically analyze problems, gather and process information, and evaluate alternative solutions.

Instructor's actions: set research-oriented tasks, organize teamwork in small groups, and facilitate discussions.

Role of digital visualization: to enhance clarity in data analysis, hypothesis testing, and pattern recognition.

Examples of tools include Maple (for building mathematical models and creating visual graphs), GeoGebra (for creating dynamic geometric representations), and Go-Lab (for integrating simulations and data collection).

3. Constructive–Activity Stage

Objective: to enable students to design their own digital products and implement team-based projects.

Instructor's actions: facilitate teamwork, support role distribution, and provide methodological and technical guidance.

Role of digital visualization: to function as a shared platform for coordinating actions, integrating results, and visually monitoring progress.

Examples of tools: Blender (for 3D modeling), Tinkercad (for creating interactive models), and cloud platforms such as Miro or Notion (for visual project planning and task tracking).

4. Reflective–Evaluation Stage

Objective: to analyze outcomes, assess the level of soft-skills development, and plan further individual growth.

Instructor’s actions: organize public project presentations, facilitate reflection sessions, and provide individualized feedback.

Role of digital visualization: to present project results in an accessible, visually interpretable format that supports assessment of teamwork and argumentation.

Examples of tools include interactive presentations in Canva or Prezi, as well as visual analytics dashboards in Power BI or Google Data Studio, which are used for displaying processed data.

In summary, the phased implementation of the model within the educational process ensures the systematic and manageable development of soft skills. The consistent use of digital visualization at each stage enhances learning outcomes and increases students’ engagement in collaborative work.

4.4. Tools and resources to support the model

The effective implementation of the model for developing soft skills in future STEM teachers through a visual-digital approach is possible only with the systematic use of modern digital tools and resources that provide visualization, interactivity, and collaborative engagement in the learning process. Based on an analysis of international and Ukrainian STEM education practices, the following groups of tools and resources have been identified.

1. Software for Mathematical and Scientific Modeling

These tools are used to create symbolic, numerical, and visual models that enable students to analyze processes, test hypotheses, and make predictions. Examples include Maple, a computer algebra system for symbolic and numerical computations, graphing, and mathematical modeling; GeoGebra, a dynamic mathematical environment for interactive geometric, algebraic, and statistical modeling; and PhET Interactive Simulations, a collection of online simulations in physics, chemistry, mathematics, and biology (https://phet.colorado.edu).

Case: students in a pedagogical university are tasked with modeling the trajectory of a ball in a physics experiment. Using Maple, they build mathematical equations and graphs of motion, and then verify them in PhET by adjusting the angle and velocity of the throw. During the discussion, the team analyzes discrepancies between theoretical and simulated data, developing critical thinking and argumentation skills.

2. Tools for 3D Modeling and Visualization

These programs enable the creation of three-dimensional representations of objects and processes for instructional and research purposes. Examples include Blender, a professional 3D modeling and animation software; Tinkercad, a web-based platform for basic 3D modeling and 3D printing preparation; and SketchUp, a tool for architectural and engineering visualization.

Case: In a “Methods of Teaching Physics” course, a student team creates a 3D model of a simple electrical circuit in Tinkercad. One student designs the layout of components, another focuses on visual design, and a third prepares a teaching guide for classroom use. The model is then printed on a 3D printer and used as a hands-on demonstration during a laboratory session.

3. Virtual and Mobile Laboratories

These environments allow students to conduct experiments virtually or with mobile equipment. Examples include Go-Lab, a platform that provides access to online laboratories and inquiry-based learning scenarios (https://www.golabz.eu); Mobile Planetarium, a digital complex for 360° visualization of astronomical phenomena; and Labster, a VR-based virtual STEM laboratory.

Case: In an “Astronomy” course, students work with a mobile planetarium to prepare a team lecture for high school students on solar eclipses. Using 360° projection, they visualize the motion of the Moon and Earth, explain the mechanics of the phenomenon, and integrate the materials into a teaching module.

4. Platforms for Teamwork and Project Management

These tools facilitate planning, role distribution, and coordination in group projects. Examples include Miro, an online whiteboard for collaborative ideation; Notion, a versatile platform for project organization and documentation; and Trello, a visual task management system using boards and timelines.

Case: during an interdisciplinary STEM project, “Energy-Efficient Classroom”, students use Miro to create a mind map of ideas, Trello to track task completion, and Notion to store shared documents and visual materials. The instructor monitors team contributions in real time and provides formative feedback.

5. Interactive Presentation and Visualization Services

These platforms enable the clear and engaging presentation of team results. Examples include Canva for creating infographics and multimedia slides, Prezi for dynamic, zoom-based presentations, and Power BI or Google Data Studio for interactive data visualization.

Case: A student team presents the results of their project, “The Impact of Air Pollution on Adolescent Health,” using Google Data Studio. Their interactive dashboard includes maps, graphs, and charts that the audience can explore and filter during the presentation. This enhances the persuasiveness of arguments and promotes discussion.

6. Technical Equipment and Hardware Solutions

Hardware tools expand the potential of digital visualization, including VR/AR headsets, Arduino and Raspberry Pi microcontrollers, and 3D printers.

Case: within an “Engineering Technologies” course, students design a prototype Smart Greenhouse. Using Arduino, they program automatic irrigation and temperature control, model the greenhouse in Blender, and print the prototype casing on a 3D printer. The final product is presented in a VR environment simulating real-world functionality.

Altogether, the integration of these digital tools and resources ensures that the development of soft skills among future STEM teachers is closely tied to authentic, hands-on, and collaborative learning experiences.

4.5. Organizational and methodological recommendations for implementing the model in the educational process

The effective implementation of the model for developing soft skills in future STEM teachers through a visual-digital approach requires systematic organizational and methodological solutions. These solutions must ensure coordination among university administrators, instructors, and students, as well as the sustainability of the model amid the ongoing modernization of higher education.

To successfully implement the model, it is essential to incorporate dedicated modules or topics on digital visualization and team-based STEM projects into curricula; establish interdisciplinary collaboration among instructors (for example, joint teaching between computer science and physics faculty); and develop methodological materials that include task examples and case studies utilizing the visual-digital approach.

Case: within the master's program "STEM Education", a course titled "Visualization of Scientific Data in STEM Education" is introduced. The course is integrated across several disciplines and concludes with a team project in which students create an interactive 3D model of a physical phenomenon in Blender and defend their work publicly.

Successful implementation of the model also requires access to modern technical infrastructure, high-performance computers, VR/AR devices, 3D printers, a mobile planetarium, and Arduino kits; licensed software (Maple, GeoGebra, Blender, Tinkercad, Go-Lab); and continuous professional development of instructors in the use of digital tools and team-based learning methods.

Case: the university signs an agreement with software providers, gaining access to educational licenses for Maple and Blender, and organizes annual training workshops for instructors on using virtual laboratories and mobile planetarium technologies.

To encourage active participation of both students and faculty, institutions should implement a system of recognition and incentives (certificates, publication of the best projects, participation in exhibitions and competitions); promote student-led initiatives through flexible assessment methods that account for individual contributions; and include real-world projects commissioned by local schools or businesses to increase practical relevance.

Case: students collaborate with a local school to design a Tinkercad model of a physics classroom equipped with interactive 3D visualizations of lab instruments. The school then uses these models for 3D printing and physical classroom setup.

For the model to remain sustainable, regular updates of software and hardware resources are necessary, along with the development of internal methodological guidelines based on project outcomes and the creation of a digital repository of exemplary student work for use as instructional material.

Case: a university department establishes an electronic repository of the best student projects featuring digital visualizations. Incoming students gain access to this repository and use its contents as inspiration and methodological support for their own projects.

In summary, the organizational and methodological implementation of the model within the educational process requires comprehensive changes in curricular design, teaching methods, technical infrastructure, and institutional culture. Adhering to these recommendations will enhance the effectiveness of soft-skills development and ensure their sustainable formation among future STEM teachers in the context of education’s digital transformation.

Conclusions to Research Results 4

The theoretical and methodological substantiation, as well as the subsequent development, of a model for fostering soft skills in future STEM teachers through a visual-digital approach, have resulted in a coherent system that integrates modern digital tools, interdisciplinary tasks, and organizational forms of educational collaboration. The proposed model is structured around four interconnected components: goal-oriented, content, procedural, and outcome-based, and is implemented in accordance with the principles of adaptability, gradual progression, interdisciplinarity, and the integration of soft skills into professional training.

The pedagogical conditions ensuring the model’s effectiveness include the integration of digital visualization into problem-based learning tasks, the organization of team interaction with clearly defined roles, the use of reflective and analytical practices based on visual materials, and the availability of adequate digital infrastructure. The application of tools such as Maple, GeoGebra, Blender, Tinkercad, mobile planetariums, and virtual laboratories like Go-Lab and PhET creates an educational environment conducive to the development of critical thinking, communication, creativity, and teamwork.

The model's implementation unfolds across four interrelated stages: motivational and orientation, analytical and exploratory, constructive and operational, and reflective and evaluative, which ensure the logical sequence and manageability of the educational process, progressively enhancing the formation of students' soft skills. The consistent use of digital visualization at each stage reinforces students' analytical engagement and promotes active collaboration within teams.

The organizational and methodological recommendations proposed within the model define directions for curricular integration, faculty development, technical support, and participant motivation. Their realization ensures both the sustainability and effectiveness of the model under conditions of educational digital transformation.

Thus, the developed model represents an innovative pedagogical framework that purposefully cultivates essential soft skills in future STEM teachers by embedding their development into professional preparation and leveraging the technological potential of the visual-digital approach. Its implementation in higher education practice will contribute to the preparation of teaching professionals capable of performing effectively in environments characterized by complex interdisciplinary tasks, digital communication, and rapid technological change.

5. Summarizing the results of the study and recommendations for the implementation of a model for the development of soft skills of future teachers of STEM disciplines

5.1. Scientific generalization of the research results

The conducted study resulted in the theoretical substantiation and development of a model for fostering soft skills in future STEM teachers through a visual-digital approach. This model integrates contemporary pedagogical concepts, digital tools, and methods for organizing collaborative activities within the higher education learning process. It is designed to cultivate essential soft skills, such as critical thinking, communication, creativity, teamwork, and adaptability, that are vital for professional performance in the rapidly evolving digital landscape of education and society.

The theoretical analysis of scientific sources revealed that, despite the abundance of studies in STEM education (Binkley et al., 2012; Johnson & Johnson, 2017; Mayer, 2009), the development of soft skills is often treated either as a byproduct of subject learning or as a separate competency line detached from disciplinary content. The proposed model addresses this gap by integrating the formation of soft skills directly into the process of mastering STEM disciplines through the use of digital visualization tools.

The model was designed based on the integration of project-based learning principles, the visual-digital approach, and interdisciplinary synthesis. Its structure includes four interrelated components: the target block, which defines strategic directions for developing soft skills; the *content* block, which combines subject knowledge with interpersonal competencies; the *procedural* block, which outlines the sequential organization of learning activities; and the *outcome* block, which contains indicators and criteria for evaluating the formation of soft skills.

A major result of the study was the identification of pedagogical conditions that ensure the model's effectiveness. These include the integration of digital visualization into problem-based tasks, the organization of teamwork with clearly defined roles, the use of reflective and analytical practices based on visual materials, and the provision of access to modern digital infrastructure and learning resources. Each of these conditions was exemplified by tools such as *Maple*, *GeoGebra*, *Blender*, *Tinkercad*, *Go-Lab*, *PhET*, and the mobile planetarium, which demonstrated measurable effectiveness in fostering students' critical thinking and teamwork skills.

A significant theoretical contribution lies in defining the stages of implementing the model within the educational process: motivational–orientation, analytical–exploratory, constructive–activity, and reflective–evaluative. Each stage was accompanied by examples of digital visualization tools and collaborative formats that ensure the consistent development of soft skills.

The obtained findings align with current international trends emphasizing the integration of digital technologies into soft skills development, while extending existing approaches through a comprehensive methodological framework tailored to the preparation of future STEM teachers in Ukraine. The scientific novelty of the study lies in constructing a holistic pedagogical system that combines the acquisition of disciplinary competences and soft skills through a visual-digital approach within an integrated educational process.

The developed model was piloted across several instructional modules in natural science and engineering pedagogy faculties. The goal of this stage was to assess the feasibility of integrating selected model components into real teaching practice and to evaluate their impact on the development of students' soft skills.

Empirical data from the pilot phase indicate positive dynamics across several dimensions. In the groups where digital visualization tools (*Maple*, *GeoGebra*, *Blender*) were combined with collaborative work on interdisciplinary projects, the average level of critical thinking measured using an adapted version of the Watson–Glaser test (Watson-Glaser Test, n.d.) increased by 12.4%, compared to a 4.8% rise in control groups.

A similar trend was observed in teamwork performance. Based on participants' self-assessments and peer evaluations (scale 1–5), the average teamwork score in pilot groups rose from 3.62 to 4.28, reflecting improved communication, role distribution, and joint decision-making.

The use of mobile planetariums and *Go-Lab* virtual laboratories showed that interactive visualizations not only facilitate comprehension of complex STEM concepts but also increase motivation for teamwork. Specifically, 78% of participants reported that the visual-digital format encouraged more active engagement in project activities.

Although these results do not constitute full-scale confirmation of the model's overall effectiveness, they demonstrate its potential and justify the need for broader implementation. The positive dynamics across key indicators suggest that integrating digital visualization tools and collaborative learning methods into professional training is a promising strategy for developing soft skills in future STEM teachers.

Overall, the study confirms the relevance and promise of the developed model as an effective framework for preparing educators who can function in digitally transformed learning environments, address complex interdisciplinary problems, and demonstrate a high level of communicative and analytical competence in their professional practice.

5.2. Recommendations for implementing the model in the educational process of higher education institutions

Implementation of the Model for Developing Soft Skills in Future STEM Teachers through a Visual-Digital Approach

The implementation of the model for developing soft skills in future STEM teachers based on a visual-digital approach requires coordinated efforts among university administrators, academic staff, and students, as well as the creation of an appropriate technical and organizational environment. Based on the study's findings, a set of recommendations has been formulated, encompassing managerial, methodological, and practical levels of implementation.

At the institutional and managerial level, it is advisable for faculty and department administrations to:

Integrate the model into the university's strategic documents, including educational development strategies, digital transformation plans, and staff development programs.

Introduce interdisciplinary modules into curricula that combine digital visualization and teamwork across multiple disciplines.

Allocate funding for acquiring licensed software and technological equipment such as 3D printers, VR/AR systems, mobile planetariums, and Arduino kits.

At the methodological level, instructors are encouraged to:

Master the use of digital visualization tools (Maple, GeoGebra, Blender, Tinkercad, PhET, Go-Lab) and systematically integrate them into their courses.

Design interdisciplinary assignments that involve collective analysis, development, and visual presentation of results.

Employ project-based learning strategies focused on long-term collaborative STEM tasks with clearly defined team roles and responsibilities.

At the practical and classroom level, effective implementation requires that educators:

Form mixed student teams across years and specializations to complete tasks simulating real-world interdisciplinary projects.

Provide ongoing feedback supported by visual materials such as prototypes, graphs, and interactive dashboards.

Organize public presentations of project outcomes in the form of exhibitions, science festivals, or STEM fairs.

For sustainable and long-term implementation, it is essential to:

Conduct regular professional development workshops for educators on emerging technologies in digital visualization.

Create an internal database containing exemplary tasks, instructional materials, templates, and student project samples.

Engage external partners, schools, industry representatives, and research institutions in joint projects to enhance the practical relevance and applicability of the model.

In summary, the proposed recommendations address all key aspects of implementing the model from strategic institutional planning to specific actions by instructors and students. Their realization ensures organizational coherence, methodological alignment, and lasting positive outcomes in applying the visual-digital approach to developing soft skills among future STEM teachers.

5.3. Prospects for Further Research and Practical Application

The obtained results and the practical implementation of the model for developing soft skills in future STEM teachers based on the visual-digital approach confirmed its effectiveness in enhancing students' critical thinking, communication, creativity, and teamwork. At the same time, the analysis of its implementation process revealed several promising directions for further scientific inquiry and methodological improvement.

A key perspective involves expanding the model's application beyond pedagogical STEM specializations to other fields that combine digital technologies and interdisciplinary approaches, such as biomedical engineering, environmental science, architecture, and design. Such an extension will enable the testing of the model's universality and the identification of domain-specific adaptations required for each professional area.

Another important direction concerns adapting the model to distance and blended learning environments. This involves developing fully online ecosystems that integrate cloud-based services, VR/AR platforms, and collaborative systems for shared visual modeling. Within this framework, it is essential to investigate how the digital readiness of both teachers and students influences the effectiveness of soft skills development.

Equally significant is the long-term monitoring of graduates who studied under this model, in order to evaluate its impact on their career advancement, capacity for innovation, and effectiveness in multidisciplinary teamwork. Such monitoring could include employer surveys, analysis of professional achievements, and graduates' self-assessments.

A further avenue of research lies in combining the model with other innovative pedagogical technologies such as gamification, adaptive learning, and artificial intelligence–driven educational support systems. The application of data analytics and machine learning algorithms could enable more precise tracking and assessment of students' progress in developing soft skills.

Ultimately, international projects that test the model across diverse educational and cultural contexts would provide valuable insights into which components of the model are universally effective and which require localized adaptation.

In summary, future research should focus on the scaling, digital enhancement, and intercultural validation of the proposed model. Such efforts will ensure its long-term sustainability and contribute to improving the quality of STEM teacher education within the global educational landscape.

Conclusions to Research Results 5

This section presents a comprehensive analysis of the research findings and a set of recommendations for implementing the model to develop soft skills in future STEM teachers, based on the visual-digital approach within higher education institutions. The theoretical generalization confirmed that the proposed model has a coherent structure integrating four interconnected components: goal-oriented, content, procedural, and outcome blocks, which together ensure the organic incorporation of soft skills development into the professional preparation of future educators.

The study demonstrated that a visual-digital approach, when embedded in project-based and interdisciplinary learning, creates favorable conditions for developing critical thinking, communication, creativity, and teamwork. The proposed model not only enhances the effectiveness of mastering disciplinary knowledge but also ensures its meaningful application in solving real-world STEM problems.

The implementation recommendations encompass administrative, methodological, and practical aspects, ensuring coherence among faculty administration, instructors, and students. Specifically, the study proposes integrating the model into institutional strategic documents, curricula, and professional development programs; designing interdisciplinary modules; adopting modern digital tools and platforms; and organizing team projects that address real stakeholder needs.

Several directions for further research were identified, including scaling the model to other disciplines, adapting it to distance and blended learning environments, conducting long-term monitoring of its impact on graduates’ professional activities, integrating it with other innovative pedagogical technologies, and testing it internationally with attention to cultural specificities.

Thus, the proposed model and accompanying recommendations constitute a scientifically grounded framework for improving the quality of STEM teacher education. They are designed to foster key soft skills within a modern digital learning environment, preparing professionals who are competitive and capable of responding effectively to technological change, working in multidisciplinary teams, and implementing innovative pedagogical practices.

Conclusions

The conducted study aimed to theoretically substantiate and develop a model for fostering soft skills in future STEM teachers, based on a visual-digital approach that integrates modern pedagogical concepts, digital tools, and organizational forms of team interaction. The results of the theoretical analysis, methodological design, and pilot testing confirmed that integrating digital visualization into the content and process of professional training significantly enhances the effectiveness of soft skills development among students of pedagogical STEM specialties.

Based on an analysis of international and national experiences, it has been established that the development of soft skills in the context of STEM education is crucial in the era of digital transformation, increasing interdisciplinarity, and the growing need for adaptation to rapid technological change. The proposed model ensures the integration of critical thinking, communication, creativity, and teamwork directly into the educational process, thereby increasing the practical relevance of the acquired competencies and the professional readiness of graduates.

The scientific novelty of the research lies in the creation of a holistic pedagogical system structured around four interrelated components: target, content, procedural, and resultative, implemented through four sequential stages: motivational–orientational, analytical–exploratory, constructive–activity-based, and reflective–evaluative. Each stage is supported by the use of digital visualization tools (Maple, GeoGebra, Blender, Tinkercad, PhET, Go-Lab, the mobile planetarium, etc.) that enhance the analytical and communicative dimensions of the learning process.

The practical significance of the study is confirmed by pilot empirical data, which demonstrate a 12.4% increase in students' critical thinking levels, an improvement in teamwork indicators (from 3.62 to 4.28 points), and a rise in motivation for collaboration among 78% of participants. These findings highlight the potential of the model for broader implementation in higher education and underscore the importance of conducting large-scale studies for its further validation.

Future research prospects include scaling the model to other academic fields, adapting it to distance and blended learning formats, integrating it with innovative pedagogical technologies, and conducting international trials considering cultural and educational differences.

Thus, the developed model and the accompanying set of recommendations constitute a scientifically grounded and methodologically robust framework designed to ensure a high level of professional preparation for future STEM teacher specialists, capable of effective performance in a digital society, collaborative work, and innovative problem-solving in their professional practice.

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