STEM Education in Canada and Ukraine: Transformations, Innovations, and Pathways for Sustainable Development

Monograph

Open Science Initiative

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First published 2025
by Open Science Initiative
10136 104 St NW, Edmonton, Alberta, Canada
T5J0B5

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ISBN 978-1-0692596-1-5
https://doi.org/10.31110/STEM-CaUk

CONTENT

EDITORS' NOTE: Why This Book Appeared at This Moment

This volume emerges at a time when education systems worldwide are undergoing profound transformations. Questions of how to prepare societies for an era defined by artificial intelligence, climate change, and digital interdependence have never been more pressing. STEM science, technology, engineering, and mathematics has long evolved beyond the boundaries of individual disciplines. It now represents a framework through which nations define their innovation capacity, competitiveness, and sustainability.

STEM Education in Canada and Ukraine: Transformations, Innovations, and Pathways for Sustainable Development is therefore more than a collective academic study. It is a bridge connecting two educational systems that, though shaped by very different historical experiences, share a commitment to progress through knowledge, creativity, and technology.

Relevance and Focus

Ukraine today stands at a crossroads of reconstruction and renewal. Its future depends on the ability to rebuild infrastructure and human capital through innovation and education. A strong STEM foundation is essential for this task, encompassing areas such as energy, biotechnology, cybersecurity, and modern engineering. The Canadian experience, by contrast, offers a model of an inclusive, sustainable, and research-driven educational system that links STEM learning with community engagement and entrepreneurship. This book brings both perspectives into dialogue, not to imitate but to understand mechanisms of success and possibilities of adaptation.

STEM education is also closely tied to the global Sustainable Development Goals. It equips learners with the competencies needed to address environmental, technological, and social challenges. The chapters in this monograph examine how principles of sustainability can be integrated into educational programs and research projects in both countries.

Scientific and Practical Contribution

The book provides one of the first comprehensive comparative analyses of STEM education in Canada and Ukraine. It reveals not only contrasts but also unexpected parallels, such as the shared challenges of encouraging women's participation in technical fields or addressing academic migration.

It unites multiple disciplines: education, pedagogy, economics, sociology, and policy studies. Such interdisciplinarity allows the contributors to examine STEM education as both a classroom practice and a national development strategy.

Importantly, this volume moves beyond diagnosis. Its chapters offer practical insights and proposals for policymakers, educators, and institutional leaders seeking to align STEM programs with sustainable growth and social inclusion.

Position in the Global Discourse

Internationally, STEM research often focuses on a single country or regional bloc. Comparative studies bridging distinct socio-economic and cultural contexts remain rare. This monograph fills that gap.

It brings Ukrainian educational research into the global conversation while simultaneously expanding the understanding of how sustainability and innovation can be connected through pedagogy. It is designed as a foundation for further studies, both empirical and theoretical, as well as policy-oriented, that may arise from the dialogue it opens.

In Closing

STEM Education in Canada and Ukraine is a call to action. It reminds us that the future does not arrive automatically; it must be built. Education, rooted in scientific inquiry and human creativity, is the foundation of that future.

For Ukrainian readers, the book offers models and inspiration for rebuilding through innovation. For Canadian and international audiences, it provides a vivid example of how transformation takes shape under pressure. For researchers, it opens new comparative perspectives; for practitioners, it serves as a guide for action.

Together, these contributions affirm a shared belief: that quality, innovative, and socially responsible education in science and technology is the surest path toward a sustainable and human-centered future.

INTRODUCTION

Olena Semenikhina

The monograph "STEM Education in Canada and Ukraine: Transformations, Innovations, and Pathways for Sustainable Development" summarizes the results of long-term research by Ukrainian and Canadian researchers aimed at exploring the evolution, conceptual foundations, and practical models of implementing STEM and STEAM education. The need for this publication arises from the large-scale transformation of both countries' educational systems in the era of digitalization, rapid technological development, ongoing war, and climate challenges, as well as the rethinking of education's role in achieving the Sustainable Development Goals. The STEM approach is increasingly seen not merely as an instructional technology, but as a philosophy of integrating science, engineering, technology, mathematics, and the arts into a coherent system for developing competencies that define the human and social capital of the future.

This monograph seeks to address the lack of comprehensive comparative works that systematically analyze national STEM education models, trace the dynamics of scientific research and pedagogical innovation, and evaluate their practical effectiveness. It draws on bibliometric, pedagogical, and empirical data, encompassing both the macro level (educational policy, institutional practices, digital transformation) and the micro level (methodology, pedagogical experimentation, technological environments).

The first chapter provides a conceptual foundation for understanding STEM education as a multidimensional field of research and pedagogy. Based on an analysis of more than 20,000 publications indexed in the Web of Science database, this study offers a comparative overview of the Canadian and Ukrainian STEM/STEAM research landscapes, outlining national development strategies, institutional support systems, levels of digital integration, and priorities in pedagogical innovation. Researchers V. Shamonia and O. Semenikhina demonstrate that the Canadian system is characterized by institutional maturity, a focus on inclusivity, and the integration of Indigenous knowledge and humanistic dimensions into STEM education, whereas the Ukrainian model displays rapid digital renewal, flexibility, and an exceptional capacity for innovation despite the constraints of wartime conditions.

The second chapter brings together studies highlighting innovative pathways for implementing STEM/STEAM across diverse educational institutions. O. Hrechanovska presents a model for integrating the STEAM approach into technical universities through humanities courses, demonstrating its effectiveness in harmonizing technical and cultural thinking and fostering creativity and value orientation among future engineers. Researchers I. Shyshenko, T. Lukashova, and O. Pypka demonstrate how the use of Maple can enhance the training of future mathematics teachers for implementing STEM education, particularly through the creation of a digital-analytical environment that develops modeling and research skills among students. Together, these works confirm that STEM and STEAM function as mechanisms for the renewal of higher professional education, uniting technical precision with humanistic vision and creative thinking.

The third chapter focuses on STEM-oriented teacher preparation. H. Rozlutska, S. Hirniak, and Ya. Petryna substantiate the relevance of integrating STEM elements into the professional education of future primary school teachers, presenting experimental results that demonstrate improved readiness to apply innovative teaching methods. A. Yurchenko's study reveals how the integration of project-based learning and digital visualization fosters critical thinking, teamwork, and communicative flexibility among future STEM educators. A. Melnyk's work introduces a model of STEAM-oriented vlogging as a tool for developing the professionally oriented communicative competence of pre-service foreign language teachers, where digital tools and interdisciplinary projects are embedded in the linguodidactic process of professional training. Together, these studies form a unified vision of modern teacher education, in which STEM serves as a vehicle for developing flexible and creative professional competencies.

The fourth chapter expands the analytical scope by integrating STEM/STEAM into specialized education and the paradigm of sustainable development. The study by A. Zhukova, M. Halchenkova, Ya. Dziuba and S. Demikhova examine the role of the foreign language teacher in military education, where the STEAM approach fosters interdisciplinary thinking, analytical, and communicative skills among future officers, and contributes to the humanization of the professional environment. The work of A. Truten and S. Tolochko analyze the development of ecological competence among senior school students through STEM learning and project-based methods. The authors convincingly demonstrate that combining environmental education with the STEM approach creates the necessary conditions for achieving sustainable development goals and nurturing environmentally conscious youth.

This monograph is intended for scholars, educators, students, policymakers, and all those seeking to gain a deeper understanding of the patterns shaping STEM education as a driving force of educational, technological, and cultural modernization across different countries. It aims to serve as a platform for continued dialogue between national educational communities, facilitating the exchange of effective practices and strengthening the Canada-Ukraine partnership in the fields of research and education.

Chapter 1

THEORETICAL AND METHODOLOGICAL FOUNDATIONS OF STEM EDUCATION DEVELOPMENT

1.1. STEM Education Landscapes: A Comparative Bibliometric and Pedagogical Overview of Canada and Ukraine

Volodymyr Shamonia, Olena Semenikhina

***Abstract**. This chapter provides a comprehensive comparative analysis of STEM education in Canada and Ukraine, integrating bibliometric mapping, qualitative content analysis, and comparative synthesis. Drawing on over 21,000 publications indexed in the Web of Science, including more than 850 Canadian and 85 Ukrainian works, the study examines national trajectories, institutional priorities, and pedagogical innovations. The findings demonstrate that Canada has solidified its position as a global leader, bolstered by mature research infrastructures, comprehensive policy frameworks, and extensive international collaborations. Canadian STEM education emphasizes teacher preparation, equity, diversity, and inclusion (EDI), the integration of Indigenous and multicultural knowledge systems, and a strong tradition of informal learning environments such as science museums and afterschool clubs. Emerging trends highlight digital pedagogy, immersive technologies, and gamified approaches, situating STEM as a vehicle for civic engagement, sustainability, and social justice. In Ukraine, STEM education has evolved rapidly, despite economic and wartime challenges, reflecting the country's adaptability and innovation under constraint. Pedagogical universities integrate STEM modules into teacher training, emphasizing visualization, modeling, and competency-based approaches. Practices include cloud-based platforms, augmented and virtual reality, and experimental adoption of generative AI to foster research skills and reflective thinking among pre-service teachers. Ukraine also demonstrates strong alignment with the Sustainable Development Goals (SDGs), expanding STEM into non-formal settings through STREAM centers, gamification, and project-based initiatives that extend access to underserved and displaced learners. The comparative analysis reveals complementary strengths. Canada offers institutional maturity, inclusivity, and ethically grounded pedagogy, while Ukraine exemplifies resilience, rapid digital adoption, and crisis-driven innovation. Equity and inclusion remain divergent: Canada benefits from systemic frameworks for gender and refugee support, while Ukraine continues to face acute regional and infrastructural disparities. Nevertheless, both*

DOI: 10.31110/STEM-CaUk-1.1

contexts demonstrate the potential of STEM education to act as a driver of societal transformation, whether through stability and policy coherence (Canada) or through adaptive experimentation and resilience (Ukraine). The chapter concludes that cross-national collaboration between Canada and Ukraine could generate mutually beneficial outcomes. Canada may learn from Ukraine's agile innovation cycles, while Ukraine could adapt Canada's inclusive and policy-supported models. Together, they offer distinct but complementary pathways for reimagining STEM education as context-sensitive, ethically informed, and future-oriented, capable of addressing the intertwined challenges of technological disruption, sustainability, and social resilience.

Keywords*: STEM education; Canada; Ukraine; comparative analysis; teacher education; digital transformation; visualization; inclusive pedagogy; bibliometric analysis; educational innovation.*

Introduction

STEM education, encompassing science, technology, engineering, and mathematics, is widely recognized as a driving force behind innovation, economic development, and societal transformation in the 21st century. Across the globe, governments and institutions have intensified efforts to implement STEM programs that not only equip learners with technical knowledge but also cultivate critical thinking, creativity, collaboration, and problem-solving skills. Recent scholarly works underscore the need for integrative and context-responsive STEM models that reflect local challenges while engaging with global scientific and technological frontiers.

In the Canadian context, research highlights the expansion of STEM education into realms of ethics (Steele, 2016), the integration of Indigenous knowledge, and the adoption of transdisciplinary inquiry (Takeuchi et al., 2020). Teacher education has emerged as a pivotal site for enacting these changes, with universities designing STEM courses that promote equity, inclusivity, and socially relevant pedagogies (Babb et al., 2016; Estaiteyeh & DeCoito, 2023).

Meanwhile, in Ukraine, STEM education has become a strategic priority in the wake of digital transformation and geopolitical crisis. Studies by Semenikhina et al. (2022, 2023), Drushlyak et al. (2023), and others document the use of cloud-based platforms, modeling tools, visualization techniques, and AI-driven simulations to support future mathematics and informatics teachers. Despite resource limitations, Ukrainian educators have demonstrated remarkable resilience and innovation, positioning STEM as a vehicle for societal adaptation and recovery.

Given these trajectories, a comparative analysis of STEM education in Canada and Ukraine is timely and necessary. It enables the identification of shared priorities, divergent pathways, and complementary innovations. Such an analysis supports evidence-based dialogue on the future directions of STEM education, particularly in the context of preparing teachers and shaping inclusive, future-ready societies.

The *aim of this chapter* is to examine and compare the bibliometric landscapes and pedagogical practices of STEM education in Canada and Ukraine, with a focus on teacher training, digital integration, inclusivity, and sociocultural framing.

This chapter is structured as follows: presents a bibliometric overview of global STEM education research, highlighting publication dynamics and Canada's and Ukraine's positioning; explores STEM education in Canada, emphasizing teacher education, EDI principles, Indigenous knowledge, and digital pedagogy; analyzes STEM education in Ukraine, focusing on digital tools, modeling, AI, inclusivity, and responses to wartime challenges; offers a comparative synthesis of both national experiences, identifying overlaps, differences, and mutual learning opportunities; concludes with key insights, implications for global STEM development, and suggestions for future collaborative research.

Research Methods and Data Sources

The research presented in this chapter employs a mixed-methods approach that combines bibliometric analysis with qualitative content analysis and comparative synthesis. The aim was to explore both the scope and the nature of STEM education scholarship and practices in Canada and Ukraine. The study relied on the following data sources and methodological procedures:

1. Bibliometric Analysis. Data were retrieved from the Web of Science (WoS) database using the keyword query “STEM education” across the fields of title, abstract, and keywords. The

analysis included publication counts by year, country, author affiliation, document type, and citation metrics. A focused comparison of Canadian and Ukrainian STEM research output was conducted, with a specific focus on national trends, influential authors, and thematic areas of focus.

2. Qualitative Content Analysis. A purposive sample of peer-reviewed publications by Canadian and Ukrainian authors was analyzed to identify dominant themes, models of teacher education, pedagogical strategies, and sociocultural framings of STEM. These included recent empirical studies, conceptual frameworks, and case-based reports from national and international journals, as well as proceedings from relevant conferences.

3. Comparative Synthesis. Based on the extracted data and thematic insights, a comparative analysis was carried out to examine both convergence and divergence in STEM education priorities, practices, and innovations across the two countries. The synthesis emphasized not only pedagogical content but also the underlying assumptions about equity, inclusion, crisis response, and societal development.

The study draws on over 40 publications authored by Ukrainian researchers in the field of STEM education (2015–2025), as well as more than 30 recent studies and policy-oriented works from the Canadian context. The results were further supported by Web of Science analytics and visualized using charts and tables to illustrate publication dynamics and thematic clustering.

Findinfs

Bibliometric Landscape of STEM Education

The quantitative analysis revealed that STEM education has evolved into an interdisciplinary research area since the early 2000s, with a significant increase in publications occurring after 2010. Canada demonstrates relatively high activity (850 papers), while Ukraine is at the stage of institutionalizing STEM research (85 papers), but is actively integrating into the international space, especially through joint publications and conferences.

Bibliometric analysis serves as an effective tool for assessing the scope, dynamics, and focus areas of scientific research within a specific field. This subsection presents an overview of publication activity related to STEM education based on data retrieved from the Web of Science Core Collection (WoS). The keyword query 'STEM education' was applied to the 'topic' field (including title, abstract, and keywords), yielding a comprehensive sample of publications directly related to educational aspects of STEM.

As of August 2025, the WoS database contained 21,794 scholarly publications on STEM education (Figure 1).

Figure 1 presents the annual trend in STEM education publications from 1976 to 2025.

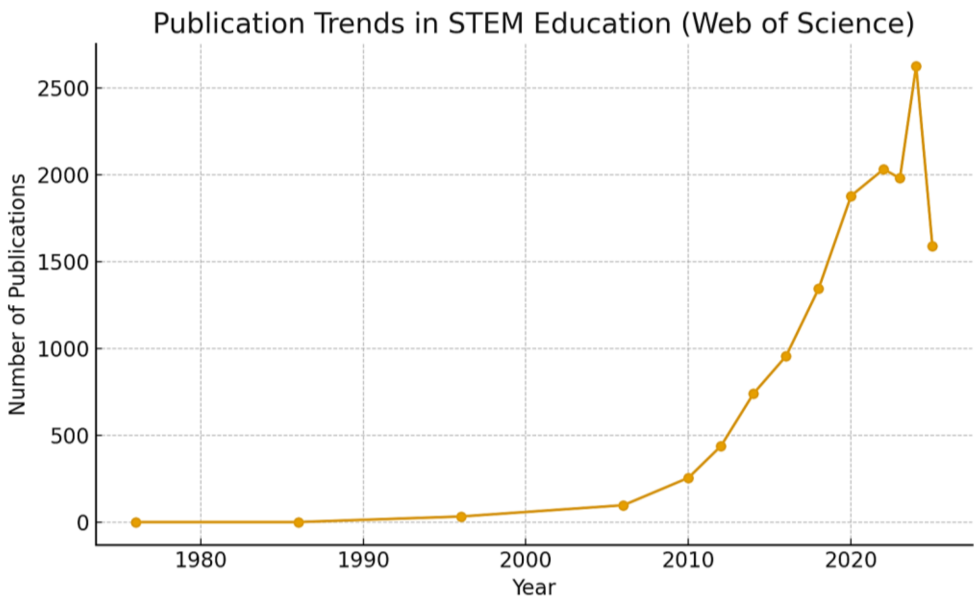

Figure 1. Publication Trends in STEM Education (Web of Science, 1976–2025)

The figure illustrates the annual number of publications indexed in Web of Science that include 'STEM education' in the title, abstract, or keywords. A significant increase in output is observed since 2010, reflecting growing scholarly interest in the field.

If the search is limited to titles only, the total is 2,638, including 82 publications associated with Canadian authors and 22 with Ukrainian authors. These figures reflect a substantial level of global interest in the topic, though with marked variability in regional representation.

Since the mid-2000s, there has been a steady increase in the number of STEM education publications. A sharp rise was observed starting in 2015, with peak outputs recorded during the 2020–2024 period, coinciding with the COVID-19 pandemic and a global shift to digital learning models. In 2024 alone, more than 2,600 works were published, while the first eight months of 2025 yielded nearly 1,600 publications. These trends confirm the consolidation of STEM education as a leading topic in educational scholarship, shaped by digitalization, labor market transformation, and global crises.

Geographically, STEM education research is represented by authors from 167 countries (Figure 2).

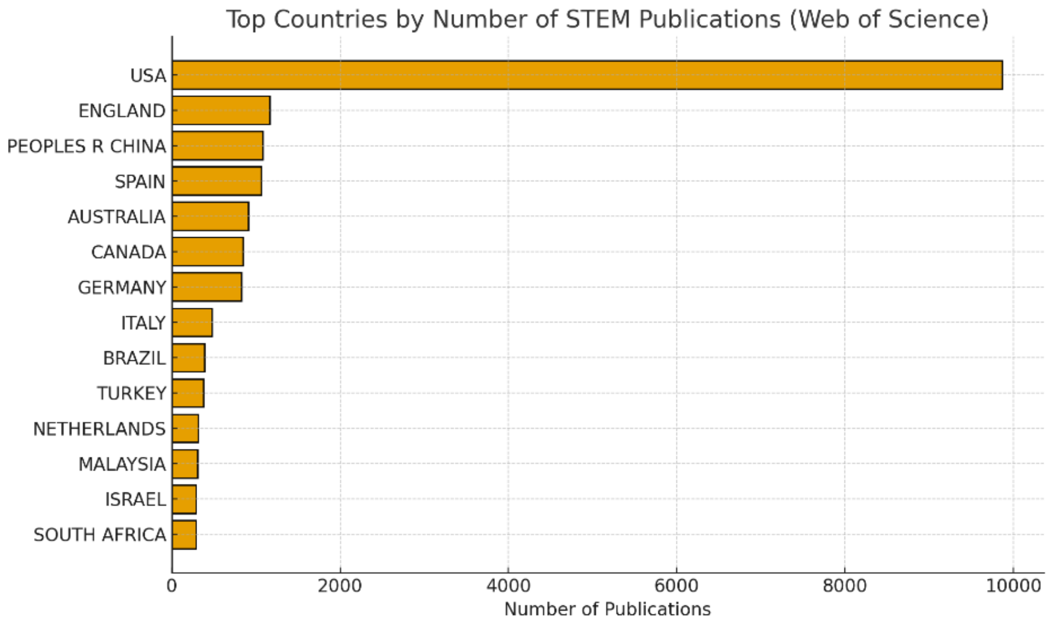

Figure 2. STEM Education Publications by Country

The leading contributors include the United States, China, Spain, the United Kingdom, Germany, and Canada. Canada ranks sixth globally with 850 publications, while Ukraine holds the 49th position with 85 publications, indicating steady but still modest integration into the global STEM discourse.

The majority of documents in the sample are research articles published in peer-reviewed journals, comprising roughly two-thirds of the total. Conference proceedings account for about 20 percent, particularly from events such as EDUCON, ICERI, and MIPRO. A smaller portion consists of review articles, book chapters, and other formats, collectively reflecting the formation of a multidimensional interdisciplinary research field.

Among the most prolific authors are Charles Henderson, Gillian Roehrig, Tamara J. Moore, Siddika Selcen Guzey, and Gabriel-Miro Muntean. These scholars represent leading universities in the United States, Ireland, and beyond. Their work focuses on integrating STEM education into school and university curricula, as well as teacher training and digital learning innovation.

The list of most cited works further illustrates the influence of foundational research. Notable among them are Kelley and Knowles' (2016) conceptual model of integrated STEM education, English's (2016) perspectives on K–12 STEM integration, and interdisciplinary teaching strategies proposed by Asghar et al. In the Canadian context, Blotnicky et al. (2018) stand out with a study on the connection between STEM career awareness and student motivation.

A key aspect of understanding the landscape of STEM research in Canada involves identifying the leading academic institutions contributing to the field. Based on data from the Web of Science, the following table (Table 1) presents the top Canadian universities and research centres ranked by the number of publications related to STEM education. This information highlights the institutional distribution of research efforts and serves as an indicator of regional academic capacity and specialization in STEM pedagogy, policy, and innovation.

This institutional breakdown confirms the dominance of large research-intensive universities, particularly the University of Toronto, UBC, and McGill, in shaping the STEM education discourse in Canada. Notably, a strong representation from both anglophone and francophone institutions (e.g., Université de Montréal) reflects the country's bilingual academic landscape.

Table 1. Canadian Institutions with the Highest Number of STEM Education Publications (Web of Science)

Rank	*Institution Name*	*Number of Publications*
1	University of Toronto	159
2	University of British Columbia	97
3	McGill University	79
4	University of Calgary	72
5	University of Alberta	52
6	University of Ottawa	48
7	University Health Network, Toronto	44
8	Western University / University of Western Ontario	42
9	Simon Fraser University	39
10	Université de Montréal	37
11	University of Victoria	29
12	Queen's University Canada	28
13	University of Waterloo	26

Furthermore, the presence of medical and research networks, such as the University Health Network, underscores the interdisciplinary nature of STEM and its applications in health and the applied sciences. These institutions not only lead national scholarly output but also play a pivotal role in setting pedagogical trends, forming policy recommendations, and training the next generation of STEM educators.

Ukrainian contributions include Kupets (2016) on the education employment mismatch and Kramarenko et al. (2019) on the use of augmented reality in mathematics instruction. To better understand Ukraine's contribution to STEM education research, it is important to examine the institutional affiliations of the most active authors. Based on publication data from the Web of Science, Table 2 below presents Ukrainian institutions ranked by the number of their publications related to STEM education. While the overall volume remains modest compared to global leaders, these institutions represent the emerging centers of expertise and innovation in the Ukrainian STEM research landscape.

Table 2. Ukrainian Institutions with the Highest Number of STEM Education Publications (Web of Science)

Rank	*Institution Name*	*Number of Publications*
1	Ministry of Education and Science of Ukraine	73
2	Dragomanov Ukrainian State University	10
3	National Academy of Educational Sciences of Ukraine	8
4	National University of Life and Environmental Sciences of Ukraine	8
5	Borys Grinchenko Kyiv Metropolitan University	7
6	State University Kyiv Aviation Institute	6
7	Kherson State University	5
8	Oleksandr Dovzhenko Hlukhiv National Pedagogical University	5
9	Taras Shevchenko National University of Kyiv	5
10	Zhytomyr Ivan Franko State University	5
11	Donetsk State University of Internal Affairs	4
12	Igor Sikorsky Kyiv Polytechnic Institute	4

Despite the relatively small number of entries compared to the Canadian or global context, the Ukrainian landscape exhibits a diverse range of institutions contributing to STEM education scholarship. The strong presence of the Ministry of Education and Science of Ukraine as the top contributor indicates the role of policy-oriented and state-sponsored research. Pedagogical universities (e.g., Dragomanov, Hlukhiv, Zhytomyr) and classical universities (e.g., Taras Shevchenko National University of Kyiv) play a leading role in STEM-related teacher training and educational innovation. Notably, technical institutions like the Kyiv Polytechnic Institute are beginning to feature more prominently, signaling growing interdisciplinary interest.

This distribution reflects both the institutional decentralization of Ukrainian research and the ongoing efforts to integrate STEM education into broader educational reforms, often under the constraints of war, economic challenges, and digital transformation. Continued growth in publication output from these institutions will be critical for establishing Ukraine's presence in global STEM education discourse.

Among the scholarly works that have had the greatest impact on the development of STEM education research, both Canadian and Ukrainian authors are prominently represented. The most cited publication is by Howard et al. (2021), which presents a meta-analysis within the framework of Self-Determination Theory and highlights the fundamental role of motivation in educational outcomes. Noteworthy among Canadian researchers are Beauchamp (2015) and Abrami et al. (2011), who have analyzed innovative approaches in teacher preparation and online learning design.

The study by Blotnicky et al. (2018), conducted in Canada, examines the relationship between knowledge of STEM careers and motivational factors among middle school students and stands out as one of the most cited empirical investigations in the field of STEM education.

On the Ukrainian side, the most frequently cited work is that of Kupets (2016), which, although focused on education–job mismatch, provides valuable insights into the challenges facing the STEM labor market. Also noted are studies dedicated to augmented reality in STEM teaching (Kramarenko et al., 2019), neuropsychological approaches to instruction (Voznyuk et al., 2021), and a terminological analysis of the concept of STEM education (Stryzhak et al., 2017).

These studies are published in journals from major academic publishers, including Springer, Elsevier, IEEE, and Taylor & Francis, as well as specialized Canadian and Eastern European journals, confirming the interdisciplinary and technology-oriented nature of the field.

In summary, STEM education has developed into a conceptually rich and interdisciplinary research domain, spanning pedagogy, psychology, ICT, engineering, and the social sciences.

Canada demonstrates sustained research activity with a focus on inclusion and pedagogical innovation. Although Ukraine’s volume of publications remains modest, the country has shown rapid growth in digital, visual, and competency-based STEM models and is increasingly integrated into international academic networks through joint publications, conferences, and experimental pedagogical initiatives.

STEM Education in Canada: Practices and Research Approaches

Canada consistently ranks among the global leaders in STEM education research, benefiting from well-established infrastructures, diversified funding, and strong international collaboration networks. Its scholarly output frequently appears in high-impact journals and is highly cited, underscoring the country’s integration into global research ecosystems (Zhan et al., 2022). This bibliometric strength provides a stable foundation for advancing innovative pedagogies and teacher preparation models.

In recent years, Canada has consolidated its position as a global leader in STEM education, not only through policy commitment and curriculum innovation, but also through the depth and diversity of its scholarly research. STEM education in Canada has evolved beyond the traditional technocratic paradigm to embody a multidimensional and critically engaged framework that integrates equity, Indigenous perspectives, digital transformation, and sustainability ethics.

A bibliometric and thematic review of Canadian publications from 2020 to 2025 reveals that teacher education remains the most actively researched and published area, accounting for approximately 28% of all scholarly contributions on STEM education during this period. This prominence reflects a national consensus that the future of STEM depends not only on student access but on educators’ preparedness to facilitate interdisciplinary, inquiry-driven, and inclusive learning environments.

Institutions such as the University of Calgary and the University of British Columbia have played a foundational role in reshaping STEM teacher preparation. For example, the Werklund School of Education has developed courses that blend core scientific content with pedagogical inquiry and reflective practice, enabling pre-service teachers to design, implement, and critically analyze STEM units across disciplinary boundaries. These courses are informed by a three-phase pedagogical model described by Tsybulska et al. (2018), which moves from collaborative inquiry to design and then to field-based implementation, emphasizing the importance of experiential learning for internalizing STEM's transformative potential.

In parallel, Canada has institutionalized Equity, Diversity, and Inclusion (EDI) frameworks across STEM teacher education. Research by Estaiteyeh and DeCoito (2023) has demonstrated that explicit training in differentiated instruction significantly enhances pre-service teachers' ability to respond to diverse learning needs and cultural backgrounds. Their findings are consistent with broader national efforts to ensure that STEM learning is inclusive, representative, and socially responsive.

Another defining element of Canadian STEM education is its commitment to multicultural and multilingual integration. Bilingualism (English–French) is not only a linguistic feature but also a pedagogical asset, as programs deliberately address cultural diversity, equitable participation, and gender inclusivity (Frontiers in Education, 2024). Indigenous perspectives are complemented by broader multicultural frameworks that recognize Canada's heterogeneous student population.

A notable feature of Canadian STEM education is its deep and sustained engagement with Indigenous knowledge systems. Scholars such as Ji (2021) and Nicol et al. (2023) highlight how land-based education, Indigenous languages, and local epistemologies are being woven into mainstream STEM programs. The Canadian Light Source (CLS) initiative exemplifies this integration, offering programming where students explore chemistry and physics through culturally situated inquiry, in partnership with Indigenous communities and elders. Such efforts shift the focus from decontextualized content to locally grounded, relational approaches to science and mathematics.

Ethical and sociocultural considerations have also become central to the Canadian STEM agenda. Building on foundational critiques by Steele (2016), recent research emphasizes STEM as a medium for civic engagement, social justice, and ecological sustainability. Nicol et al. (2019, 2023) propose a “STEM as place” framework that redefines mathematics education as a relational practice, prioritizing connections between learners, communities, and the natural environment over narrow metrics of productivity or economic efficiency. These arguments resonate with the work of Yanez et al. (2019), who advocate for production pedagogy models that empower students to become agents of change within their own sociotechnical ecologies.

Alongside these pedagogical and ethical dimensions, digital transformation has become a defining feature of STEM education in Canada. From early integration of virtual reality and clickers (Lakshminarayanan & McBride, 2015) to more recent frameworks like ACT-STEM (Wu et al., 2021), the emphasis has shifted toward developing computational thinking, data literacy, and digital fluency. Milner-Bolotin (2017) outlines a model of digitally supported inquiry in which teacher candidates engage with peer instruction, collaborative design tools, and real-time data collection, experiencing the affordances and limitations of digital environments first-hand.

Canadian STEM research also engages with questions of immigration and educational access. As Boyd and Tian (2018) demonstrate, immigrants with STEM degrees, particularly those educated outside Canada, the US, the UK, or France, often face systemic barriers to employment and professional recognition. Picot and Hou (2018) similarly note a persistent earnings gap between Canadian-born and immigrant STEM graduates, which raises concerns about both credential portability and labor equity. Responding to these concerns, Le Pichon et al. (2025) propose a comparative curriculum analysis framework for assessing the STEM readiness of refugee students and developing culturally responsive diagnostic tools. This emerging strand of research foregrounds the importance of equitable access to STEM learning across migration trajectories.

Canadian research also demonstrates a strong emphasis on informal learning environments. Science museums, afterschool clubs, and national STEM competitions are integrated into policy frameworks and supported by research–practice partnerships. These settings provide authentic contexts for inquiry, reinforce curricular learning, and expand access to STEM for underrepresented groups.

Together, these thematic strands illustrate the pluralistic nature of Canadian STEM education research (Fig. 3). While no single narrative dominates, the literature converges on several shared priorities: preparing reflective and adaptive educators, embedding STEM in ethical and cultural contexts, promoting inclusive and relational pedagogies, and leveraging digital tools to enhance inquiry and access. The Canadian case demonstrates that STEM education, when meaningfully situated, can serve not only as a conduit to economic opportunity but as a medium for critical, creative, and collective engagement with contemporary challenges.

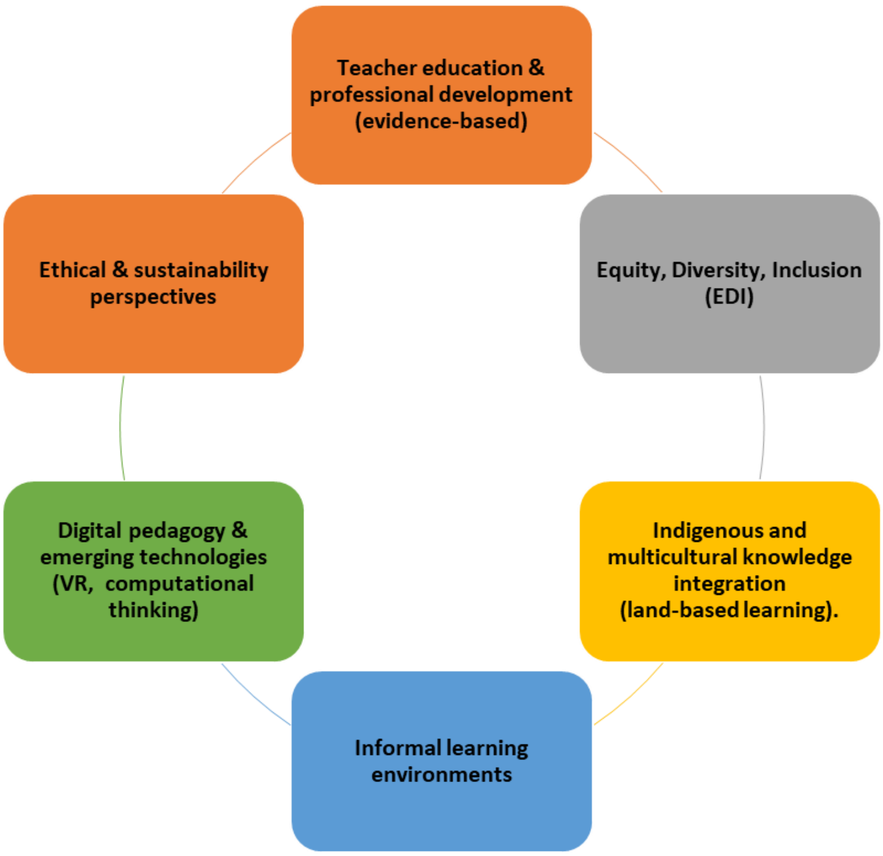

Figure 3. STEM Education Research Trends in Canada (2020–2025) with an expanded thematic focus, including informal learning environments and emerging digital innovations

This evolving landscape of STEM education in Canada demonstrates not only thematic breadth but a clear epistemological shift from standardized, discipline-driven approaches to more situated, relational, and ethically grounded models of teaching and learning. By integrating Indigenous worldviews, embracing digital and AI-powered tools, and addressing systemic inequities, Canadian educators and researchers are reimagining STEM as a means to achieve inclusive and sustainable futures. The Canadian case thus offers both a mirror and a map: a mirror reflecting the complex intersections of science, society, and identity, and a map for other nations seeking to reposition STEM education as a force for human flourishing and global justice.

Recent advances highlight Canada's exploration of immersive and gamified approaches, such as metaverse applications that create interactive STEM environments and motivate sustained engagement (Chen et al., 2023). These innovations, supported by robust infrastructure and teacher professional development, signify the country's ability to experiment with next-generation pedagogies.

STEM Education in Ukraine: Practices and Research Approaches

Ukraine's STEM education research landscape has expanded rapidly over the past five years, with bibliometric mapping showing concentration in metropolitan centers such as Kyiv and Lviv. While citation impact remains limited, international collaborations are gradually increasing, providing visibility despite scarce domestic funding and infrastructural constraints (Zhan et al., 2022; Freeman et al., 2019). Since the early 2010s, STEM education in Ukraine has undergone rapid evolution into a dynamic field, shaped by national educational reforms, technological advancements, and, in recent years, the exigencies of war. Despite enduring structural challenges, including underfunding, limited infrastructure, and the migration of academic personnel, Ukrainian researchers and educators have devised innovative practices, particularly in STEM-related teacher education. The period from 2020 to 2025 marks a decisive shift toward competency-oriented, digitally enriched, and research-informed

STEM strategies, positioning Ukraine as a responsive and experimental context within global STEM transformations.

The most prominent field of activity concerns the institutional integration of STEM in teacher training programs. Ukrainian pedagogical universities, such as Sumy State Pedagogical University, National University 'Chernihiv Collegium', and Dragomanov Ukrainian State University, have systematically integrated STEM modules into pre-service education for future teachers of mathematics, physics, and informatics. These modules emphasize dynamic visualization, mathematical modeling, algorithmic thinking, and cross-disciplinary project-based learning. Semenikhina et al. (2022) and Drushlyak et al. (2023) document how STEM is not treated as an isolated subject but rather as a vehicle for the formation of integrated methodological thinking. Moreover, this integration often relies on individualized tasks, micro-research, and simulation-based exercises, forming an early culture of educational inquiry among students.

At the policy level, Ukrainian STEM education is closely aligned with the UN Sustainable Development Goals, particularly through emphasis on student motivation, critical thinking, and public–private partnerships in education (EJSD, 2023). These initiatives position STEM not only as a curricular innovation but also as a societal tool for advancing sustainability and civic responsibility.

A second major focus lies in the digitalization of STEM learning and the active promotion of visual thinking. Cloud-based platforms, such as GeoGebra, Desmos, and Tinkercad, are increasingly used in both school and university-level instruction. Ukrainian researchers, particularly those affiliated with regional STEM laboratories, have designed numerous interactive learning scenarios that combine dynamic geometry, parametric transformations, and BYOD-based strategies such as QR code tasking and mobile simulations. These tools not only support cognitive visualization but also facilitate inclusive learning, especially for students with different learning profiles or access needs. The use of visualization is further positioned as a metacognitive tool in developing spatial reasoning and systemic problem-solving among teacher trainees. Beyond cloud-based platforms such as GeoGebra and Desmos, Ukrainian teachers increasingly experiment with augmented and virtual reality. Tools like Google Expeditions and Google Lens have been piloted to increase student motivation and support blended learning (Shapovalov et al., 2018). However, challenges persist, including limited Ukrainian-language interfaces and uneven teacher awareness, which constrain broader adoption.

Another growing vector of research is inclusive and competency-based STEM education. Ukrainian studies emphasize accessibility, adaptability, and personalization of digital STEM content to reflect the needs of students with disabilities, refugees, and learners from rural or underserved areas. Researchers such as Drushlyak et al. (2023) propose competency models that integrate media literacy, critical thinking, and collaboration into science and math instruction. Additionally, interdisciplinary and transdisciplinary efforts, particularly those aligned with STEAM frameworks, have found traction in non-formal settings such as digital camps, maker spaces, and thematic STEM festivals supported by local education authorities and NGOs. Despite progress, Ukraine continues to face persistent regional disparities and gaps in teacher preparedness for implementing systemic STEM initiatives. Surveys indicate low awareness of global STEM programs among pedagogical students and practicing teachers. These challenges underscore the need for sustained professional development frameworks that are comparable to those in Canada.

Perhaps the most experimental domain is the integration of AI and reflective technologies into pre-service STEM teacher education. Recent studies (Drushlyak et al., 2025; Semenog et al., 2025) document pilot projects in which ChatGPT and other generative tools are used to support the development of linguistic creativity, research planning, and genre-based writing among teacher candidates. AI is not merely used as a technological aid, but as a pedagogical actor, one that reshapes assessment strategies, fosters reflexive dialogue, and supports meta-level thinking about scientific communication and pedagogical modeling. Such innovations signal a growing Ukrainian contribution to AI-mediated didactic design in STEM.

The full-scale war in Ukraine since 2022 has forced educators and students into high-adaptation modes, giving rise to new resilience-oriented STEM practices. These include mobile learning kits, Arduino-based micro-infrastructures, and the use of large-scale 3D printing for rebuilding educational spaces. Pedagogical research is increasingly focusing on trauma-informed education, emotional self-regulation, and the integration of STEM into psychological support systems and urban resilience projects. This wartime context has paradoxically accelerated digital innovation and amplified international collaboration among Ukrainian STEM scholars and global partners.

Overall, Ukrainian STEM education between 2020 and 2025 exemplifies a practice-rich, adversity-informed, and digitally enhanced ecosystem. Although challenges remain, Ukrainian educators continue to demonstrate strong capacities for adaptive innovation, methodological experimentation, and collaborative knowledge building. Their practices enrich the international conversation not only through digitalization and visual tools but also by offering an example of education as a source of resilience, transformation, and hope under extreme conditions.

The thematic distribution of STEM practices in Ukraine between 2020 and 2025, as illustrated in Figure 4, highlights the field's multidimensional character and its responsiveness to both educational reforms and sociopolitical disruptions. Teacher training and institutional integration remain the structural backbone of STEM development, while digitalization and visual tools provide the primary means of pedagogical enhancement. Simultaneously, growing attention to inclusion, AI experimentation, and wartime resilience strategies reflects Ukraine's ability to reposition adversity into innovation. This complex ecosystem of practices not only mirrors global STEM priorities but also makes a unique contribution to the discourse on education as a driver of social stability, technological progress, and human-centered transformation. Ukrainian STEM education, therefore, offers a valuable case for understanding how pedagogical ingenuity can flourish even in constrained and turbulent conditions.

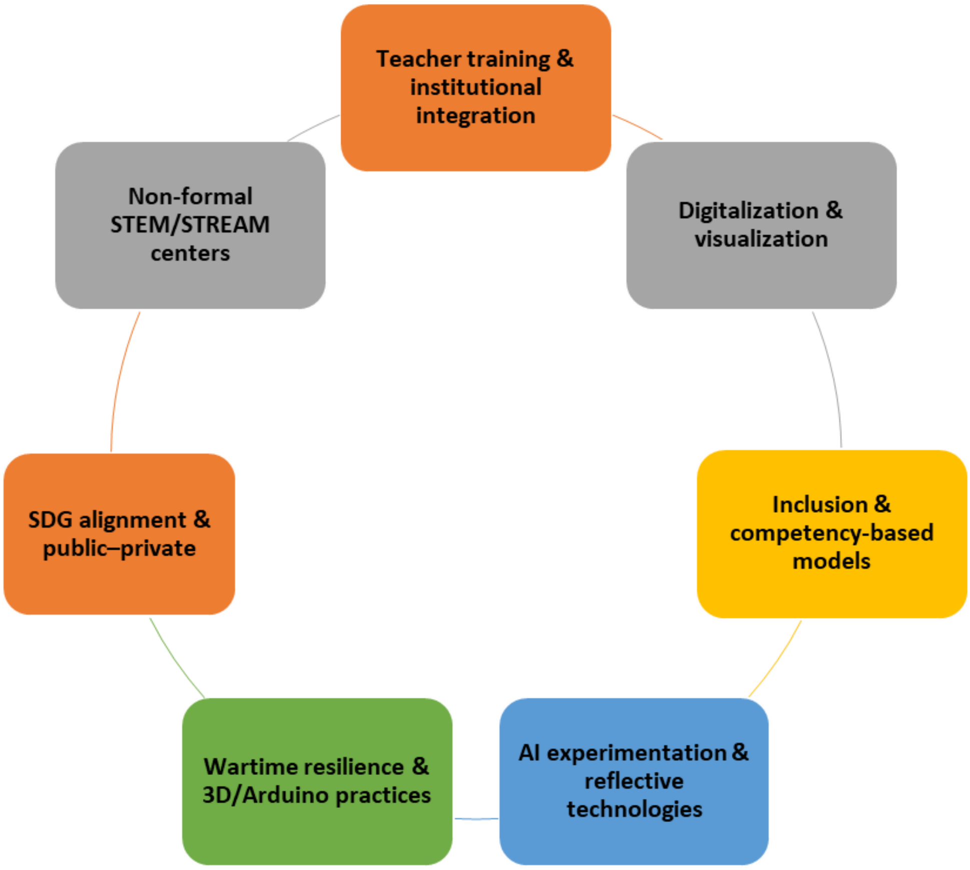

Figure 4. Thematic distribution of STEM education practices in Ukraine (2020–2025), expanded to include SDG alignment, AR/VR applications, and non-formal STEM/STREAM initiatives (Montessori, gamification).

In addition to formal education, Ukraine has witnessed the rapid emergence of STEM and STREAM centers, often supported by NGOs and municipal authorities. Innovative approaches include integrating Montessori principles and gamification techniques to foster curiosity, collaboration, and soft skills among learners (Chilvers, 2025). Such non-formal environments enrich the overall STEM ecosystem and extend access beyond traditional classrooms.

Comparative Analysis of STEM Education in Canada and Ukraine

This section presents a comparative analysis of STEM education development in Canada and Ukraine, based on the previous sections. While the two countries differ significantly in terms of geopolitical context, economic capacity, and educational infrastructure, both have demonstrated a growing commitment to advancing STEM through innovative, digitally enhanced, and socially responsive practices.

Table 3 below summarizes key comparative dimensions of STEM education in Canada and Ukraine. The table highlights divergences in research output, pedagogical models, informal education, and funding structures.

Table 3. STEM Education in Canada vs. Ukraine

Aspect	*Canada*	*Ukraine*
Bibliometric Output	Global leader, high-impact, high citation	Growing rapidly, mostly centered in key cities
Key Research Topics	Inclusivity, assessment, teacher PD, EdTech	SDGs, motivation, non-formal STEM, gamification
Pedagogical Model	Inquiry- & project-based, multicultural	Transition to constructivism, some didactics
Informal Education	Strong (museums, clubs), regular curriculum review	Rapid growth of STEM/STREAM centers; urban focus
Funding & Collaboration	Robust, international, and cross-sector partnerships	Limited, driven by individual schools/cities
Regional Reach	Nationwide, equity focus	Regional gaps: best resources in Kyiv, Lviv
Curriculum Alignment	Frequent updating, policy-driven innovation	Ongoing reform, emphasis on SDGs

A radar plot (Figure 5) synthesizes six dimensions along which STEM education in both contexts may be compared: policy and governance, equity and inclusion, digital integration, teacher training, ethical and cultural framing, and crisis-driven innovation. The radar chart is complemented by a comparative table for detailed analysis.

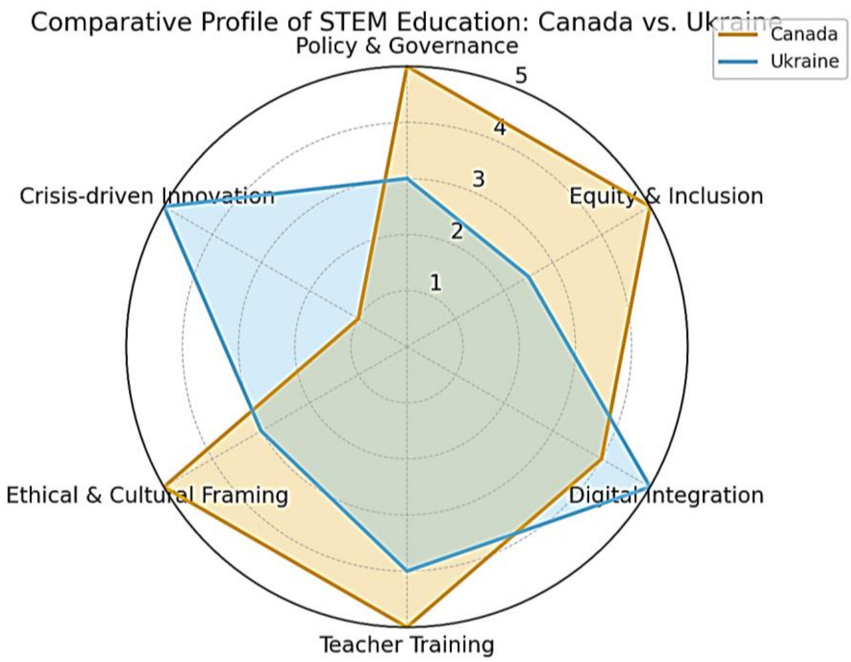

Figure 5. Comparative Profile of STEM Education: Canada vs. Ukraine

Canada exhibits strong performance across policy, inclusion, ethics, and teacher preparation. With stable funding, decentralized governance, and sustained policy efforts, Canadian institutions have successfully integrated STEM within broader educational goals, including environmental sustainability, social justice, and Indigenous reconciliation. Teacher education programs routinely address equity, interdisciplinary integration, and the ethical implications of scientific literacy.

Ukraine, by contrast, demonstrates its strengths in digital integration, methodological innovation, and adaptability in crisis situations. The widespread use of cloud-based tools, dynamic visualization platforms, and mobile learning technologies, accelerated by the war, has created a fertile ground for experimentation. While Ukraine's centralized governance and limited funding present challenges, these constraints have catalyzed the design of creative tasks, personalized learning, and AI-assisted pedagogy in STEM teacher training.

In terms of equity and inclusion, Canada leads with established frameworks for differentiated instruction and refugee support, whereas Ukraine is in the process of building inclusive strategies under the dual pressures of digital inequality and population displacement. Ethical and cultural dimensions are more thoroughly developed in Canadian discourse, especially through the integration of Indigenous worldviews and place-based mathematics. Ukrainian research, though less developed in this regard, is beginning to incorporate trauma-informed and resilience-centered pedagogies. Equity and inclusion remain crucial points of divergence. Canada has well-established frameworks for differentiated instruction, gender mainstreaming, and refugee support, supported by a significant body of empirical research (Zivot et al., 2020). In contrast, Ukraine continues to grapple with sharper gender and regional inequities, with fewer systemic interventions and a limited evidence base (Zhan et al., 2022).

The final comparison dimension, crisis-driven innovation, highlights Ukraine's unique contribution to global STEM education. The war has forced institutions to redesign educational delivery, incorporate trauma-sensitive approaches, and utilize technology in unprecedented ways. This stands in contrast to Canada, where crisis response has not been a dominant theme in STEM education research.

Taken together, the comparative profile suggests complementary strengths. Canada offers a stable, mature, and critically reflective STEM ecosystem that is well-aligned with humanistic and ecological values. Ukraine, meanwhile, provides a living laboratory of resilience, agility, and digital transformation under pressure. Collaboration between the two contexts could yield mutual benefits: Canada can learn from Ukraine’s rapid innovation cycles, while Ukraine could draw on Canadian experience in inclusive policy design and ethical framing.

Another notable difference lies in the ecosystems of knowledge production. Canadian researchers publish predominantly in high-impact international journals, shaping global STEM discourse (Li & Xiao, 2022). Ukrainian outputs, by contrast, remain concentrated in conference proceedings and local journals, which affects citation impact and visibility. These disparities highlight structural inequalities in research capacity, but also underscore Ukraine’s potential for growth through international partnerships and funding support.

The radar chart visually underscores the divergent yet complementary trajectories of STEM education in Canada and Ukraine. Canada's strengths lie in its institutional stability, long-standing policy frameworks, and integrated equity and ethics agendas. Ukraine, in contrast, demonstrates exceptional adaptability, with innovation largely driven by necessity and accelerated through crisis. The juxtaposition of these profiles reveals valuable opportunities for cross-contextual learning. While Canada may offer structural models and ethical guidance, Ukraine contributes with agile pedagogical experimentation, rapid digital adoption, and a resilience-based orientation. Together, they represent distinct but equally vital contributions to the global evolution of STEM education.

Discussion and Outlook

Reconceptualizing STEM Education: From Instrumentalism to Human-Centered Integration

The comparative analysis of STEM education in Canada and Ukraine suggests a significant paradigm shift in both contexts: STEM is no longer confined to its technical or economic roots but increasingly positioned as a multidimensional framework that incorporates equity, ethics, interdisciplinarity, and sustainability. This is particularly evident in Canadian research, where STEM is framed through ethical imperatives (Nicol et al., 2023), Indigenous epistemologies (Ji, 2021), and inclusive pedagogies (Estaiteyeh & DeCoito, 2023). Ukraine, by contrast, demonstrates an agile reconfiguration of STEM in response to educational disruptions, notably through digital visualization (Semenikhina et al., 2022), AI-assisted creativity (Drushlyak et al., 2025), and resilience-oriented instructional design during wartime.

In addition to formal schooling, informal and non-formal STEM environments have emerged as critical spaces for innovation and equity. An important dimension that emerges from the comparative analysis is the role of informal and non-formal learning environments. In Canada, science museums, afterschool clubs, and national competitions are systematically integrated into the STEM ecosystem and supported by long-term policy frameworks and research–practice partnerships. In Ukraine, non-formal STEM and STREAM centers, often organized by NGOs or municipal authorities, have become vibrant hubs for experimentation, introducing Montessori methods and gamification. While Canada exemplifies structural stability and curricular integration of informal STEM learning, Ukraine illustrates how grassroots initiatives can extend access and inspire curiosity even under constrained conditions.

These trajectories illustrate how STEM education evolves not only in alignment with global pedagogical trends but also in response to localized challenges. The transformation is not merely curricular; it is conceptual, shifting from STEM as a means of skill acquisition to STEM as a medium for critical engagement and societal transformation.

Bibliometric Trends and Research Gaps

The bibliometric data confirms a dramatic growth in global and national interest in STEM education, with a more than tenfold increase in publications between 2010 and 2024. Canada ranks among the top six countries globally, with 850 indexed publications, while Ukraine, although occupying the 49th position, shows a steep upward trajectory, particularly since 2020. Notably, over 60% of Canadian publications explicitly address teacher training, equity, or place-based learning, whereas Ukrainian research is concentrated around digital tools, modeling environments, and educational adaptation under duress.

Despite the increase in volume, several research gaps remain. For instance, very few studies from either country employ longitudinal designs to track the long-term impact of STEM interventions. Similarly, while AI and data science are frequent topics in Ukrainian practice-oriented studies, Canadian scholarship remains more focused on theoretical and cultural critiques. There is limited empirical research comparing the effectiveness of AI-assisted instruction versus traditional STEM pedagogies across both systems.

Another trend that warrants attention is the alignment of STEM education with the United Nations' Sustainable Development Goals (SDGs). Canadian approaches primarily frame sustainability through ethical, ecological, and place-based perspectives, connecting learners with environmental responsibility and civic engagement. Ukraine, by contrast, adopts SDG-oriented strategies at the policy level, positioning STEM as a tool for addressing urgent social challenges such as resilience, equity, and sustainable urban development. This contrast highlights how distinct socio-political contexts influence the orientation of STEM education toward sustainability.

Structural and Thematic Complementarities

The radar comparison (Figure 5) reveals areas of complementary expertise. Canada demonstrates institutional maturity in STEM policy, social justice integration, and ethical reflection, while Ukraine leads in agile digitalization, rapid pedagogical adaptation, and mobile/remote learning strategies. These profiles suggest mutually beneficial opportunities for knowledge exchange.

For example, Canadian teacher education programs could incorporate Ukrainian strategies for visual task variation and micro-research in applied STEM disciplines. Ukrainian institutions, in turn, may benefit from Canadian models of sustained professional development in inclusive and differentiated instruction, particularly in multilingual or multicultural classrooms. Collaborative doctoral training, co-authorship networks, and virtual STEM labs could foster meaningful academic exchange.

Complementarities are also visible in the adoption of emerging technologies, which both countries approach in distinct ways. The expanded analysis also highlights the growing role of emerging technologies in STEM pedagogy. In Canada, immersive metaverse platforms and gamified approaches are gradually entering mainstream higher education, supported by strong infrastructure and professional development programs. Ukraine, on the other hand, demonstrates a more experimental adoption of augmented and virtual reality, cloud-based mobile simulations, and applications utilizing Arduino or 3D printing. Despite resource limitations, these innovations illustrate how technology integration can be leveraged for resilience and renewal in times of disruption.

Critical Reflections and Theoretical Implications

The divergence between Canadian and Ukrainian approaches also highlights theoretical tensions within the global

STEM discourse. Canadian literature often draws on sociocultural theory, decolonial critique, and ecological systems frameworks, emphasizing place, narrative, and relationality (Steele, 2016; Nicol et al., 2019). Ukrainian work, conversely, tends to be grounded in cognitive and systems theory, emphasizing modeling, standardization, and functional adaptation, particularly visible in work on dynamic geometry environments, computer simulations, and testable performance indicators (Semenikhina et al., 2023).

This divergence raises important epistemological questions. Revisiting the theme of equity and inclusion further illustrates these epistemological contrasts. Equity and inclusion remain central yet divergent issues across both contexts. Canada benefits from institutionalized frameworks that support differentiated instruction, bilingual programming, gender parity, and refugee support, all of which are reinforced by a robust body of empirical research. Ukraine, by contrast, continues to face acute gender and regional disparities in STEM participation, compounded by uneven access to digital infrastructure and insufficient systemic teacher preparation. These differences underscore the need for Canada to share its inclusive policy frameworks and for Ukraine to adapt them to local socio-economic realities. Should STEM education prioritize cultural relevance and social cohesion, or technological competence and adaptability? Can these objectives be harmonized in cross-contextual models of teacher education? The dialogue between Canadian and Ukrainian perspectives may offer not only answers, but entirely new research questions at the intersection of pedagogy, ethics, and digital futures.

Outlook and Future Research Agenda

The comparative insights presented above invite a broader synthesis of the Canadian and Ukrainian cases. Taken together, these insights suggest that Canada and Ukraine embody complementary approaches to STEM education. Canada provides a model of institutional maturity, cultural inclusivity, and ethically grounded STEM pedagogy. Ukraine provides a living example of digital resilience, wartime innovation, and the integration of experimental AI. The juxtaposition of these trajectories reinforces the argument that STEM education is not monolithic but context-sensitive: it can either stabilize and expand existing systems, as in Canada, or catalyze transformation under crisis, as in Ukraine.

Cross-national collaboration between the two systems could therefore be especially fruitful, combining stability with agility, ethical grounding with rapid innovation.

Building on the identified trends, we propose several priority directions for future research and bilateral cooperation:

1. Longitudinal Evaluation: Systematic tracking of STEM teacher education models over multiple cohorts in both countries, with attention to inclusive and digital competencies.

2. AI-Mediated Pedagogy: Cross-cultural examination of AI's role in STEM instruction, including co-design of ethical frameworks for classroom use.

3. Place-Based and Trauma-Informed STEM: Integration of Indigenous and post-crisis models of STEM education to foster culturally grounded and psychologically safe learning.

4. Digital Ecosystems for Bilateral Collaboration: Creation of virtual STEM labs, co-authored open-access teaching modules, and multilingual repositories of visual and adaptive tasks.

5. Assessment and Metrics: Development of common indicators to evaluate STEM-related soft skills, ethical reasoning, and reflexive thinking among students and teachers.

So, STEM education in Canada and Ukraine offers contrasting yet complementary narratives: one grounded in institutional continuity and critical reflection, the other in urgency, adaptability, and digital innovation. Together, they challenge linear or universalist models of educational development. Instead, they suggest that effective STEM education must be context-sensitive, ethically informed, and future-oriented. As global crises, ranging from climate change to technological acceleration and armed conflict, reshape educational priorities, the Canadian and Ukrainian experiences offer instructive templates for resilience, relevance, and renewal in STEM education.

Conclusion

The comparative study of STEM education in Canada and Ukraine, supported by bibliometric and qualitative analyses, reveals both global alignments and local specificities that are shaping the future of education in the digital and post-industrial age. This chapter demonstrated that while STEM education has become a near-universal priority, its implementation, framing, and perceived purposes vary significantly across sociopolitical contexts.

First, the bibliometric analysis confirms the dynamic growth of STEM-related scholarship globally, particularly over the last decade. Canada ranks among the top contributors, reflecting strong institutional, governmental, and scholarly engagement with STEM as a driver of innovation and societal equity. Although Ukraine holds a modest position in global bibliometric rankings, its publication activity in STEM education has grown steadily, particularly in areas such as digital pedagogy, teacher training, and competency development.

Second, the review of Canadian practices reveals a well-established infrastructure for STEM education reform, characterized by long-term investments in teacher education, the integration of Indigenous knowledge systems, and a deep engagement with issues of ethics, equity, and sociocultural responsiveness. STEM in Canada is not limited to content mastery; it is framed as a medium for fostering citizenship, ecological awareness, and interdisciplinary inquiry. The Canadian model underscores the importance of EDI (Equity, Diversity, Inclusion) and place-based learning as foundational elements of future-oriented education.

A notable finding concerns the role of informal and non-formal STEM learning environments. In Canada, science museums, afterschool clubs, and citizen science initiatives are firmly embedded in policy frameworks and curricular innovation, reinforcing the inclusivity and sustainability of STEM education. Ukraine, by contrast, demonstrates a rapid expansion of STEM and STREAM centers, often initiated by NGOs, municipalities, and grassroots networks. These centers experiment with Montessori methods, gamification, and project-based activities, illustrating how non-formal learning can broaden access and cultivate curiosity even under resource-constrained or crisis conditions.

Third, the Ukrainian experience showcases adaptability, innovation under constraint, and rapid digital transformation. Amidst economic and geopolitical challenges, Ukrainian educators have leveraged open digital platforms, modeling tools, and AI technologies to create resource-efficient and pedagogically effective STEM learning environments. The emphasis on visual thinking, inclusive digital access, and the development of critical competencies reflects a pragmatic response to contemporary needs, including those shaped by wartime realities. Moreover, Ukrainian STEM research increasingly reflects a commitment to aligning with international standards and networks, positioning the country as an active participant in global educational discourse.

The analysis also highlights how STEM education is becoming increasingly aligned with broader societal agendas and technological advancements. Ukraine has explicitly integrated STEM education into its pursuit of the United Nations Sustainable Development Goals, positioning it as a vehicle for sustainability, resilience, and civic responsibility. Canada frames sustainability more through ethical and ecological perspectives, linking STEM with place-based education and environmental stewardship. At the same time, both contexts are engaging with emerging technologies: Canada is institutionalizing immersive platforms such as the metaverse and gamified higher education, while Ukraine is pioneering experimental applications of augmented/virtual reality, Arduino, and large-scale 3D printing. Together, these trends highlight the dual importance of sustainability and innovation in shaping future-ready STEM ecosystems.

Fourth, the comparative analysis highlighted both convergence and divergence. Both countries prioritize interdisciplinary teaching, teacher capacity-building, and the integration of modern technologies. However, the philosophical and structural underpinnings differ: Canada's model is supported by stable governance and a long history of progressive education policy, whereas Ukraine's model is marked by resilience, urgency, and innovation born of necessity. This juxtaposition presents a valuable opportunity for mutual learning. Canada can benefit from Ukraine's agility in digital and crisis-driven pedagogies, while

Ukraine may draw from Canada's experiences in institutionalizing inclusive and ethically grounded STEM education.

Overall, the comparative insights suggest that Canada and Ukraine contribute complementary strengths to the global STEM landscape. Canada offers a model of systemic stability, inclusive policy frameworks, and ethically grounded pedagogy, while Ukraine exemplifies resilience, digital adaptability, and rapid innovation in the face of crisis. Cross-national collaboration could therefore be especially beneficial: Ukraine could draw on Canadian experience in institutionalizing equity and policy design, while Canada could learn from Ukraine’s agile adoption of digital tools, experimental AI applications, and resilience-oriented pedagogies. This complementarity demonstrates that effective STEM education is not universal but context-sensitive, shaped by local needs, resources, and cultural priorities, yet enriched through international dialogue and cooperation.

In conclusion, STEM education in both contexts proves to be not only an academic or economic imperative but also a reflection of broader societal values and priorities. As the world grapples with environmental challenges, technological disruption, and political instability, the role of STEM education in shaping responsible, capable, and critically minded citizens becomes more important than ever. Cross-national dialogue, research partnerships, and co-developed frameworks between countries such as Canada and Ukraine can serve as catalysts for more equitable, adaptive, and socially relevant models of STEM education worldwide.

Limitations of the Study

Despite the comprehensive nature of this analysis, several limitations should be acknowledged. First, the bibliometric component was based solely on data from the Web of Science database. As a result, it does not fully reflect the scope of national publications in Ukraine, particularly those published in Ukrainian-language journals not indexed in WoS. Therefore, the true extent of STEM-related research in Ukraine may be underestimated.

Second, the data exhibit a certain asymmetry: Canada, with its well-established institutional research infrastructure, has produced significantly more STEM publications. This creates a disparity in the comparative analysis, although the quality and contextual value of Ukrainian publications, especially those focused on crisis-responsive strategies and digital innovations, demonstrate substantial potential not always captured by quantitative metrics.

Additionally, the analysis of STEM practices in both countries was based primarily on academic publications and policy documentation. It did not include empirical measurement of student or teacher outcomes. Future research could benefit from comparative studies that examine learning outcomes, pedagogical effectiveness, and the long-term impact of various STEM teacher education models.

Finally, although the data set includes publications up to 2025, the rapidly evolving context, particularly in relation to digital transformation, AI integration, and the war in Ukraine, demands continuous monitoring and reevaluation of trends. The dynamic nature of these developments limits the predictive power of current analyses and highlights the need for ongoing, longitudinal research.

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Chapter 2

INNOVATIVE APPROACHES TO STEM/STEAM IMPLEMENTATION IN EDUCATIONAL INSTITUTIONS

2.1. Implementation of the STEAM Approach in a Technical University Through Humanities Courses and Interactive Learning

Olena Hrechanovska

***Abstract**. The issue of the STEAM approach and its effectiveness in the training of future specialists in technical fields (engineers) remains quite controversial today. Therefore, this study proposes an authorial vision for integrating the STEAM approach into the educational process and outlines prospects for its development in a technical university through humanities courses. The subsection "Step by Step: Transforming Technical Education through STEAM Approaches" presents the theoretical foundations of STEM and STEAM education, drawing on the experiences of foreign and Ukrainian scholars. A set of functions that the STEAM approach performs in the educational process is defined. The subsection "Formation of Engineering Competencies in the STEAM Space: Methods and Technologies" analyzes teaching methods and technologies, their classification, and the experience of implementing optimal strategies for realizing the STEAM approach by both international and domestic educators. The third subsection, "Methodology of Integrating the STEAM Approach into the Teaching of Humanities in Technical Universities," describes the methodology of conducting classes in the course "Psychology of Personality" based on the STEAM approach, using interactive (active) teaching methods and technologies, as well as the specifics of their assessment. The paper also presents prospects for further implementation of the STEAM approach through the author's developed course "Cultural Studies of Mathematics." The conclusions highlight the problems encountered during the implementation of the STEAM approach through the lens of humanities education and the use of interactive (active) educational technologies in the formation of future specialists in technical fields.*

***Keywords**: STEAM approach, interactive (active) educational technologies, future specialists in technical fields, humanities disciplines.*

DOI: 10.31110/STEM-CaUk-2.1

Introduction

In the context of social transformations and global challenges of the 21st century, technical higher education faces issues not only in the domain of professional training but also in developing innovative, creative, value-oriented, and critical thinking among future engineers. Society continues to seek optimal educational forms of integration and interdisciplinarity to help students better understand their future profession at both theoretical and practical levels, as well as on cultural and spiritual levels. The STEM education model (Science, Technology, Engineering, Mathematics) remains both relevant and valuable, as it emphasizes the natural sciences, engineering, technology, and mathematics, proving its effectiveness in fostering scientific and technological progress.

Both international and Ukrainian scholars have contributed to the study of implementing the STEM model in education. Among foreign researchers are M. Wolfmeyer, T. Kelly, D. Clements, J. Lupinacci, J. Maeda, J. Knowles, J. Sarama, and N. Chesky. In Ukrainian pedagogy, the topic has been addressed by V. Boichenko, N. Honcharova, L. Hrynevych, A. Kokarieva, O. Liashenko, V. Miziuk, N. Morze, I. Slipukhina, O. Stryzhak, A. Ovchatova, H. Onopchenko, O. Onopchenko, N. Polikhun, K. Postova, and others.

Despite the extensive research on implementing STEM in educational processes, current pedagogical paradigms are increasingly emphasizing art, culture, creativity, and the humanization of technical education. The problem, nevertheless, is not limited to developing creativity among future engineers. It also concerns professionals in other fields, since the absence of a connection between engineering and cultural foundations can threaten the very essence of engineering thinking, leading to the dehumanization of technological inventions. This destructive tendency is already visible: many technological achievements that could serve humanity, such as drones, are used in warfare rather than agriculture, mining, or other peaceful industries.

Therefore, it is essential to preserve humanity, morality, national identity, and cultural distinctiveness among future engineers through higher education institutions. These institutions should serve not only as centers of knowledge but also as spaces of culture and spirituality, shaping a new elite capable of advancing both technological and cultural progress, while learning to integrate humanitarian aspects into professional knowledge, skills, and practices. For this reason, we consider it necessary to extend the STEM model by adding creative foundations, thus implementing the STEAM approach in the educational process of technical universities.

Global socio-economic realities, multicultural dynamics, and military conflicts are reshaping how STEAM approaches are perceived, emphasizing the interconnection between technology and culture. Over recent decades, various transformations of STEM have been explored: STEAM (STEM + Arts), STEMM (STEM + Medicine), and STREAM (STEM + Reading/Writing + Arts). Today, we believe the integration of STEAM (STEM + Arts) into engineering education is particularly relevant, alongside the search for optimal teaching methods and technologies to ensure its effective implementation.

The implementation and methodological development of the STEAM approach in training students have been examined by numerous researchers worldwide, including S.-Y. Byun, J. Katz-Buonincontro, D. Clements, J. Maeda, J. Michael, J. Sarama, H. Park, E. Perignat, M. Schlesinger, and J. Yakman. In Ukrainian pedagogy, this issue has been addressed by A. Brovchenko, O. Isaieva, V. Tymenko, S. Poida, H. Shainer, O. Yatsyna, and others.

The STEAM approach to training future specialists requires a rethinking of traditional pedagogical strategies in technical higher education. There is an increasing demand for effective teaching forms and methods that can meet the professional needs and competencies of future engineers. Whether innovation is indispensable or traditional approaches can be transformed to achieve similar outcomes remains an open question. Rapid technological progress often outpaces the educational system’s ability to implement new methods, rendering many innovations short-lived, particularly in the training of engineers.

This study offers an authorial perspective on selected aspects of integrating the STEAM approach into the training of future engineers.

Step by Step: Transforming Technical Education through STEAM Approaches

The technologization of society has contributed to the improvement of educational paradigms, making STEM approaches increasingly popular. Initially, STEM was designed to harmonize theory and practice. Scholars emphasize that such approaches in education are crucial for maintaining sustained interest in research, encouraging professional mastery, and developing creativity and independence (Ovchatova, 2021). They also enhance motivation for studying science and mathematics, as well as for mastering the fundamental competencies required to solve problems in fields such as engineering, medicine, ecology, and information technology (Chornomorets & Vasylenko, 2023).

There are currently different perspectives on defining STEM education. Some researchers describe it as "a pedagogical approach that integrates diverse directions" (Buriak, 2018); others as a synthesis of science and art that fosters creativity (Kolomiiets, 2017); or as a modern tool for developing a learner's creative abilities, where the process begins with play and gradually leads to the acquisition of new knowledge and practical skills (Shulykin, 2015). In the context of technical higher education, STEM is perceived as "a contemporary educational phenomenon that enhances students' understanding of disciplines... aiming to prepare them for the effective application of acquired knowledge to professional challenges, particularly through improving higher-order thinking skills and developing competencies" (Podliesnyi & Tarasov, 2019). Another definition views it as "an approach based on the principles of interdisciplinarity, the integration of theoretical and applied components, the digitalization of educational content, and the development of soft skills among future specialists in technical fields" (Kravchenko et al., 2025).

Foreign scholar M. Wolfmeyer emphasized that, in its early stages, the STEM movement served its initial purpose of ensuring economic and military competitiveness (Wolfmeyer, 2015).

A group of international researchers later applied Karen Barad's concept of agential realism to describe the ontological dimensions of STEM education. Agential realism combines epistemology and ontology, positing that reality does not exist independently of the observer but is formed through interaction between the observer and the observed object. The authors identified three overlapping dimensions of this ontology: STEM as an apolitical educational trend, STEM as a Eurocentric economic policy, and STEM as a discursive episteme (Wolfmeyer, Lupinacci, & Chesky, 2017). This framework allows STEM to be perceived in multiple dimensions, revealing its systemic complexity. Such an approach is particularly valuable when discussing the development of competencies among future engineering professionals whose education is grounded in STEM principles yet requires conceptual expansion toward broader horizons.

In Ukraine, the development of STEM education began in 2015, when the Ministry of Education and Science of Ukraine hosted a roundtable discussion on the prospects of STEM education and its implementation in the national educational system. A series of measures were approved for 2016-2018, including four priority areas: legal and regulatory support; improvement of normative documents; development of regulations on STEM education and integrated curricula for special courses and electives; creation of methodological resources for various types and levels of educational institutions; and organization of academic events such as conferences, seminars, symposia, webinars, and competitions. A milestone in this development was the adoption of the Concept for the Development of Natural and Mathematical (STEM) Education, followed by the issuance of the Ministry's Order "On the Establishment of a Working Group on the Implementation of STEM Education in Ukraine" (2016).

Currently, Ukraine actively implements STEM education through specialized centers and laboratories, which provide the conditions for experimental work and enable students of all ages to engage in STEM-based studies.

Thus, when considering the implementation of STEM in the educational process, it can be stated that this approach represents a system of knowledge capable of combining and integrating different domains into a coherent professional direction. Moreover, when necessary or as needed, it can remain flexible and responsive to social, scientific, and educational changes.

Increasingly, certain factors demand a new perspective on how STEM is implemented in technical education (specifically within Ukrainian higher technical institutions). These factors have contributed to the expansion and humanization of the concept. One such factor is the development of professionally essential skills, which in psychological and pedagogical literature are commonly divided into soft and technical skills. Soft skills are mostly associated with psychological and personal characteristics, while technical skills relate to cognitive and technical abilities.

International researchers classify soft skills as non-technical, intangible, and personal abilities that encompass qualities such as leadership and conflict mediation attributes not rooted in technical expertise (Ballarm, 2015). Other scholars emphasize the significance of soft skills in enhancing communication, interpersonal relationships, management efficiency, and ethical or moral decision-making, including persistence, problem-solving, teamwork, self-discipline, and time management (Robert W. Gaines & Mecca B. Mohamed, 2014).

As previously discussed in our study on developing soft skills among future specialists in technical fields (Hrechanovska, 2024), contemporary Ukrainian education is structured around competencies outlined in the educational and professional programs of technical universities. Among these competencies are:

- the ability to think abstractly, analyze, and synthesize;
- project development and management skills;
- teamwork and cross-cultural collaboration;
- environmental responsibility;
- clear and unambiguous communication of professional knowledge and arguments to both experts and non-specialists, including students;
- proficiency in information and communication technologies;
- lifelong learning and continuous professional development;

– adaptability and readiness to act in new situations;
– creativity and idea generation;
– problem identification and problem-solving;
– the ability to communicate effectively with representatives of various professional groups and industries;
– independence and leadership within group settings;
– analytical reasoning and synthesis of complex information.

Analyzing these professionally significant competencies and personal traits of future engineers reveals that they cannot be formed solely through technical knowledge, skills, or abilities. They constitute the foundation of engineering practice, which must be integrated with cultural, social, and humanitarian disciplines such as cultural studies, psychology, ethnopsychology, and pedagogy. Consequently, STEM should be viewed as a process requiring transformation, expansion, and integration with artistic and humanistic dimensions principles at the core of STEAM education.

Nevertheless, some international scholars argue that expanding STEM in this direction may weaken its technical focus and dilute its original intent (Clements & Sarama, 2021). This makes the introduction of STEAM into higher education both complex and debatable. Nevertheless, we concur with E. Perignat and J. Katz-Buonincontro, who view STEM and STEAM as interdependent educational constructs, each having emerged in response to the other (Perignat & Katz-Buonincontro, 2019).

The position of researcher Georgette Yakman, an engineering and technology educator with a master's degree in education, is particularly noteworthy. Yakman is recognized as the founder of the STEAM educational framework, which she developed in 2006, with its implementation beginning in 2007. Her approach is compelling because she did not seek to reinvent or replace the existing STEM structure but rather to systematize and enrich it. Her studies demonstrated how the inclusion of the humanities provides a contextual dimension to STEM education. Yakman emphasizes that STEAM is "more than the combination of fine arts with STEM, as the humanities add the questions of 'who' and 'why' to the 'what' and 'how' of STEM" (Yakman, 2019).

This approach humanizes STEM by shifting it toward cultural and ethical awareness, fostering creativity, and promoting a more holistic understanding of technological education. It also expands the methodological possibilities of teaching, enhances interdisciplinary connections, and supports the development of learner-centered education.

Some foreign scholars argue that the relationship between STEM and STEAM is natural and evolutionary, with one emerging as a response to the appearance or development of the other (Perignat & Katz-Buonincontro, 2019).

An insightful contribution to the conceptualization of STEAM was made by Jefferson Rodrigues-Silva and Ángel Alsina in their analytical and methodological study "Conceptualising and Framing STEAM Education: What Is (and What Is Not) This Educational Approach?" The authors focus on the history, epistemology, and differences between STEM and STEAM, proposing an analytical framework that clarifies what STEAM is not. Their position, which we share, is that STEAM does not pose a threat to STEM education nor diminish the value of technical disciplines.

According to their findings, STEAM is not:

– An evolution of STEM, since it emerged from a creative and philosophical tension rather than as a linear progression;
– A single teaching methodology, because it employs multiple methodological approaches and builds upon them instead of replacing them. STEAM may rely on one methodology, while others enhance its interdisciplinarity (Jefferson Rodrigues-Silva & Ángel Alsina, 2023);
– A synonym for interdisciplinarity, as "interdisciplinarity refers to dialogue among disciplines in general, whereas STEAM represents such dialogue within a specific cluster of disciplines defined by the acronym, aiming to modernize curricula" (Moore et al., 2014);
– An attempt to erase disciplinary boundaries through transdisciplinarity. On the contrary, this educational approach is firmly grounded in the disciplines that constitute it (Jefferson Rodrigues-Silva & Ángel Alsina, 2023).

The researchers identify two essential conditions for STEAM education: interdisciplinarity and inclusion of the core disciplinary domains represented in the acronym. They emphasize that the term STEAM disciplines explicitly refers to the set of knowledge areas encompassed by Science, Technology, Engineering, Arts, and Mathematics.

Rodrigues-Silva and Alsina also draw a distinction between STEAM education and STEAM activity. They define STEAM education as "an educational approach that promotes interdisciplinary teaching of STEAM disciplines through their respective sets of practices," while a STEAM activity or lesson is "a practical form of interdisciplinary teaching that integrates at least two STEAM disciplines" (Jefferson Rodrigues-Silva & Ángel Alsina, 2023).

In Ukrainian pedagogy, a number of scholars do not emphasize a strict distinction between STEM and STEAM, viewing them instead as educational approaches that function as "an integrative pedagogical technology based on the combination of content from the natural sciences, technology, engineering, mathematics, as well as the arts and socio-humanitarian disciplines for organizing the educational process" (Polikhun et al., 2023). Ukrainian researchers also argue that meaningful progress in education can be achieved only through the integration of the arts with the natural sciences, technology, engineering, and mathematics. The implementation of the STEAM approach, therefore, enriches and elevates STEM education to a new level, preparing modern students for innovative and productive professional activity (Kuzmenko, 2020).

In higher education pedagogy, scholars investigating STEAM education view it as a priority over traditional instruction, emphasizing that such an approach prepares graduates to be competitive in the labor market. According to Isaieva (2022), "STEAM education focuses on solving real-life problems or performing practical tasks, which ensures the acquisition of skills for the practical application of knowledge."

Ukrainian scholars generally conceptualize STEAM education as a comprehensive educational approach that integrates the disciplines represented in the acronym to foster well-rounded, creative, analytical, and practical abilities in students. According to Bocharova and Dorosh (2023), this methodology aims to prepare students for problem-solving through interdisciplinary learning that encourages innovative and critical thinking, teamwork, and adaptability.

Bocharova and Kudriavtseva (2024) identify several core goals and advantages of STEAM education:

– Critical thinking development – analyzing information, applying scientific methods, and engineering design to solve problems;
– Creativity and innovation – integrating the arts to foster creative thinking and innovative decision-making;
– Interdisciplinary learning – connecting various disciplines to help students see the relationships among different fields and apply integrated knowledge in real-world contexts;
– Practical application – employing project-based learning and hands-on activities;
– Future readiness – developing flexibility and adaptability for work in rapidly changing technological environments.

Having analyzed the scientific literature on the integration of STEAM into higher education, we conclude that the issue remains insufficiently explored, particularly in the context of technical universities and the professional training of engineers. We concur with several international scholars who argue that STEAM is not an evolution of STEM, nor a methodology, nor a synonym for interdisciplinarity (Jefferson Rodrigues-Silva & Ángel Alsina, 2023; Moore et al., 2014). These conceptual ambiguities make the implementation of STEAM in technical universities a challenging endeavor.

Discussions about STEAM are often approached cautiously and do not fully reveal the depth and potential of this approach. Most attention is given to STEAM in institutions that focus on the arts or related disciplines, whereas technical universities tend to implement it more conservatively, emphasizing the technological aspects while underestimating the equal importance of the sciences and arts within the model.

In our view, the balanced interaction among all STEAM disciplines is crucial. Such an equilibrium enables students to understand how different domains interact and how the STEAM framework contributes to the development of essential competencies. This approach ensures the integrative nature of learning, where each discipline is revealed through the lens of practical application, creative thinking, and interdisciplinary collaboration. Nevertheless, the inclusion of the arts component in STEAM, while valuable, should be considered with caution: its application in technical higher education may not always be pedagogically justified or contextually relevant.

Researchers identify several key objectives of STEAM education in technical universities, which include (Isaieva, 2022): the development of competencies demanded by the labor market; readiness to address complex and multifaceted challenges that often involve contradictory situations; the ability to accurately assess problems and make timely decisions; effective interpersonal interaction through empathy toward the end-user or team members; communication skills across diverse age groups; the creation of a positive and collaborative atmosphere characterized by patience and respect; conflict resolution skills; and cognitive flexibility mental agility that enables rapid shifts in reasoning and the capacity to examine a problem or object from multiple perspectives simultaneously.

Additionally, STEAM education aims to foster the comprehensive development of the individual, shape value orientations, meet students' needs and interests, and cultivate a holistic scientific worldview along with scientific, technological, cultural, ecological, communicative, and social competence through knowledge acquisition. It aims to develop a morally responsible personality capable of making independent and ethical choices, fostering lifelong learning, promoting respect for work, and supporting personal and professional self-determination (Isaieva, 2022).

Within the educational process, the STEAM approach performs several interrelated functions, among which the following are particularly significant:

Motivational function. It stimulates students' interest in acquiring knowledge that may not directly relate to their specialization, but, when applied, enriches professional understanding through practical, creative, interactive, and project-based tasks.

Integrative function. It combines various fields of knowledge into a unified educational context, fostering interdisciplinary thinking and helping students connect theoretical and applied dimensions across disciplines.

Competence-based function. It supports the development of key and professional competencies, as well as future skills, engineering thinking, creativity, critical and analytical reasoning, communication, and collaboration.

Innovative technological function. It serves as a driver of educational transformation, uniting engineering and artistic thinking, introducing innovative teaching methods and technologies, and promoting technological creativity, adaptability to digital changes, and flexibility in professional knowledge.

Practice-oriented function. It bridges theory and practice through interactive and project-based learning, enabling students to solve real-world problems and create modern technical or artistic products.

Cultural integrative function. It harmonizes technical and humanitarian components of education by linking artistic, cultural, and technical thinking. This function enhances aesthetic awareness, intercultural tolerance, and emotional intelligence, fostering the ability to understand the cultural dimension of technical activity and to design products that are not only functional but also socially meaningful and culturally grounded.

Thus, the implementation of the STEAM approach in technical universities creates opportunities to rethink traditional teaching methods and technologies, to redesign learning content in line with modern challenges, and to cultivate in students a holistic understanding of intersectoral connections that link science, technology, engineering, the arts, and mathematics into a coherent and human-centered educational paradigm.

Formation of Engineering Competencies in the STEAM Space: Methods and Technologies

Today, the STEAM approach is positioned as an innovative educational paradigm that integrates scientific, technical, engineering, cultural-artistic, and mathematical components to create a holistic learning environment. STEAM-oriented education focuses on practice-based, project-based, problem-oriented, and learner-centered learning, activating not only cognitive processes but also influencing the emotional and value dimensions of the individual. It fosters teamwork, decision-making in non-standard situations, and the ability to design one's own educational trajectory.

When addressing the training of future specialists in technical fields, researchers emphasize that STEAM education is an essential component of engineering preparation. Therefore, creative thinking should be nurtured from school through diverse activities involving information and communication technologies, research-based learning, and project work (Hrybiuk, 2015).

The choice of teaching methods and technologies in higher education remains a key issue across disciplines, and various classifications and interpretations exist in pedagogical literature. Therefore, it is crucial to determine which are most effective for implementing the STEAM approach in training future engineers.

To clarify this, it is necessary to distinguish between learning methods and technologies. The term "method," derived from the Greek, literally means "path" or "way." In education, it denotes a path toward achieving a goal, a way of organizing and directing activity. Accordingly, a teaching method is understood as an organized form of interaction between the teacher and the student, aimed at achieving educational objectives (Aleksiuk, 1981). Bartmańska (2006) describes it as a means of achieving a goal, a planned course of instruction that defines the strategy of the teacher's pedagogical activity.

In Ukrainian pedagogy, methods of learning are viewed as a binary system of techniques, tools, and sequential actions performed by both the teacher and the learner to acquire knowledge, skills, and competencies, as well as to achieve educational and developmental goals (Honcharenko, 2003). Thus, methods can be considered components of a broader pedagogical technology.

Scholars analyzing the difference between technology and method emphasize two main characteristics of technology: orientation toward a specific result and the capacity to design the future learning process. Unlike methods, a technology is a structured, reproducible system; it is not inherently variable, although specific elements can be adapted or excluded (Pometun & Pyrozhenko, 2002).

In its original sense, the term technology was borrowed from the technical sciences, where it referred to a structured system of knowledge about organizing and executing production processes. Since the early 20th century, it has been adopted in pedagogy as the concept of "pedagogical technology," which came to mean an integrative process combining people, ideas, tools, and organizational strategies for analyzing problems of planning, implementation, evaluation, and management of all aspects of learning (Pometun & Pyrozhenko, 2004).

According to the Encyclopedia of Education (2008), pedagogical technology is understood as a means that transforms the educational process in an institution into a purposeful and organized activity involving all participants of the learning process.

In the context of the STEAM approach, this interpretation of pedagogical technology is particularly relevant, as it underscores the systemic, goal-oriented, and integrative nature of educational design qualities essential for forming the engineering competencies of modern students through interdisciplinary, creative, and practice-driven learning experiences.

A number of scholars argue that a learning technology is a "strictly algorithmized set of procedural and methodological actions performed by the teacher, along with the didactic tools used, which ensures effective learning activity of the student and the achievement of the projected outcome of the didactic cycle." Educational technologies, according to these authors, also include "methods and forms of organizing learning activity, means and tools of instruction, assessment and evaluation of knowledge acquisition, and procedures for correction and feedback."

Researchers emphasize that the essence of the term "learning technology" should rest upon a rigid algorithm of techniques, methods, and instructional strategies that guarantee the achievement of learning goals. They highlight the keywords algorithm, guarantee, and goal, insisting on a clear algorithmic sequence of actions and the assurance of a final result. This position aligns with our perspective, particularly in their interpretation of learning technology in a didactic context as a structured interaction between participants in the educational process.

Scholars have also proposed a structure of the technological learning process, comprising a hierarchy of interconnected stages: attention formation, motivation creation, goal presentation, activation (recall) of relevant prior knowledge, stimulation and guidance of learning activity, motivation of learning outcomes, verification of correctness of results, feedback through testing and necessary correction, and final criterion-based evaluation of outcomes (Lebedyk et al., 2020).

Undoubtedly, this structure can be effective; at the same time, as education involves human interaction, outcomes are not always predictable. Therefore, we believe that algorithms must remain flexible and adaptive in practice, especially within interdisciplinary frameworks such as those used in implementing the STEAM approach. The human factor introduces variability that necessitates pedagogical responsiveness and creativity rather than mechanical replication.

Ukrainian researchers identify educational technologies as one of the key tools used by teachers in their professional practice. They perform a special integrative function, serving as a pedagogical mechanism through which other instructional elements, such as communication, content, methods, techniques, and forms of organization, are applied and interconnected (Pometun, 2007). In this sense, technology influences all processes essential to knowledge acquisition and assessment, linking together the cognitive, emotional-value (affective), and physiological dimensions of the learner's experience.

We thus regard educational technologies as integrative systems that unite autonomous yet harmoniously functioning components, methods, forms, and instructional tools within the structure of a lesson. As for the purpose, objectives, and efficiency of using such technologies, we consider these aspects indispensable to any educational process, for without them, no meaningful pedagogical action can occur.

In modern pedagogy, numerous classifications of educational technologies have been proposed. One of the most detailed and systematized is that of I. Dychkivska (2001), who structured various types of instructional technologies. Building upon her typology, we analyzed these categories through the lens of STEAM integration into the preparation of future specialists in technical universities.

Structural-logical educational technologies involve goal setting, task formulation, methodological procedures, diagnostics, and assessment of learning outcomes. This resembles the algorithm proposed by Lebedyk et al. (2020), although we believe such structures must remain flexible and adaptable to transformation within STEAM-based education.

Integrative technologies encompass interdisciplinary and cross-subject integration, which lies at the heart of the STEAM paradigm.

Game-based technologies represent a crucial stage in STEAM implementation, as gamification enhances creativity, motivation, and emotional engagement.

Computer-based technologies serve as indispensable tools for conducting interdisciplinary activities, particularly in training the next generation of engineers. They promote understanding of the "human-technology" interaction and its social, ethical, and psychological implications.

Dialogic technologies focus on creating a communicative and cooperative learning environment, emphasizing subject–subject relations and collaboration among all participants of the educational process.

Instructional technologies encompass structured educational procedures and cognitive algorithms, such as testing, psychological and pedagogical training, and problem-solving sessions, designed to stimulate both intellectual and emotional engagement.

In her influential article “Teaching Methods for the 21st Century”, J. Cox (2025) argues that traditional teaching approaches are no longer effective for contemporary students, as they fail to meet the cognitive and social demands of modern education. This discrepancy has led to the emergence of new teaching methodologies or innovative versions of older strategies. According to Cox, educators now employ advanced technologies to expand students’ learning opportunities, and she highlights a range of innovative teaching approaches essential for contemporary teachers:

Active learning – engaging students through activities, group work, and discussions. This approach is student-centered, allowing students to participate in decision-making and thereby deepening their understanding and retention of the material.

Blended learning – a hybrid model combining traditional in-person teaching with technology-enhanced and online learning tools.

Inquiry-based learning, grounded in research practices, reverses the traditional “teacher explains–student listens” paradigm. Students formulate their own questions, cultivating curiosity, critical thinking, and research skills.

Cooperative learning – a student-oriented model based on teamwork, shared responsibility, and collective problem-solving. It develops independent thinking and collaboration skills.

Differentiated instruction – the use of multiple teaching methods to present the same content at varying levels of complexity, taking into account individual learner needs, styles, and abilities.

Culturally responsive teaching – aimed at establishing a shared understanding with students from diverse cultural backgrounds, fostering an inclusive learning environment that respects students’ values and experiences.

Trauma-informed teaching – focuses on creating safe, supportive environments and acknowledges the impact of trauma on students' behavior and academic performance.

Social-emotional learning – prioritizes the development of emotional intelligence, empathy, and interpersonal communication skills.

Gamification – the integration of game mechanics into the learning process to enhance motivation, engagement, and creativity.

Flipped learning – a reversal of traditional instruction, where students acquire new knowledge outside the classroom (e.g., through digital materials) and apply it in class through discussion and problem-solving.

Project-based learning – emphasizes real-world problem-solving, critical thinking, collaboration, and communication, enabling students to apply knowledge in meaningful and practical contexts.

The approaches outlined by Cox (2025) align closely with the principles of STEAM education, as they all emphasize active engagement, interdisciplinarity, creativity, emotional intelligence, and learner autonomy. Their implementation in technical higher education can significantly strengthen the development of engineering competencies, ensuring that future engineers are not only technically proficient but also adaptable, innovative, and socially responsible professionals.

The author's approach to contemporary educational practices appears highly valuable and timely to us. Nevertheless, when implementing the STEAM model, a distinctive feature emerges: the integration of cultural-artistic dimension into the technical discipline environment. This process requires not only technological innovation but also pedagogical sensitivity to the humanistic dimensions of learning.

Therefore, we propose our own definition of educational technologies that incorporate cultural and artistic aspects. We define them as an effective and comprehensive psycho-pedagogical synthesis of methodological approaches, organizational forms, and didactic tools, grounded in cultural and educational values, as well as in both innovative and traditional achievements of pedagogy. These technologies remain effective but evolve dynamically in response to technological progress, students' needs, psychological characteristics, and the specific professional orientation of an institution.

In this view, such technologies are implemented within the educational process of technical universities to promote the acquisition of knowledge, the development of practical skills and abilities, and the cultivation of competencies essential for professional work, self-development, and self-actualization of future engineers. By embedding artistic and cultural dimensions into the technical learning space, they contribute to the formation of reflective, ethically responsible, and socially conscious professionals capable of harmonizing innovation with human values.

Methodology for Integrating the STEAM Approach into the Teaching of Humanities in Technical Universities

In our practice of teaching humanities disciplines at a technical university, we implemented a variety of educational technologies to integrate STEAM approaches into the educational process. Particular attention was devoted to integrating cultural and artistic components into technical education. Our pedagogical work combined both innovative and traditional educational technologies, selecting those that proved most effective in helping students acquire new knowledge.

We placed a strong emphasis on interactive (active) educational technologies, including:

– non-simulative developmental methods (problem-based and interactive lectures, seminars, problem discussions, brainstorming sessions, debates, analyses, workshops, expert surveys, small-group work methods);

– simulative developmental methods (case studies, solving production-related tasks, simulation exercises, simulation training);

– game-based technologies (business and role-playing games, game-based project design);

– project-based learning (group project activities);

– training-based formats (group training sessions, classes incorporating training elements) (Hrechanovska, 2020).

While this set of educational technologies can be used in teaching virtually any discipline, our approach went further by integrating the Cultural and Educational Art Center (CEAC) located at Vinnytsia National Technical University into the study of humanities. The CEAC is a complex of museums dedicated to fine and decorative-applied arts. It includes eight educational art laboratories covering various themes such as classical art, decorative arts, modernism, sculpture, socialist realism, and folk iconography. We regarded the CEAC as an essential element in integrating STEAM approaches within the educational process of the technical university.

The integration of STEAM principles was implemented during the study of the course "Psychology of Personality" with second-year bachelor's students. The challenge in teaching this discipline lies in the fact that technically oriented students often lack interest in subjects they perceive as unrelated to their future professional activities. This often creates barriers to their ability to recognize the interconnection between humanities, technical disciplines, and cultural knowledge. To address this, we attempted to link students' professional (technical) knowledge with psychological and cultural understanding.

Since "Psychology of Personality" is an elective course, it can be assumed that the integration of STEAM elements occurred among students who were already interested in psychology. Our actions, therefore, aimed to help them perceive how psychological and cultural knowledge interrelates with their professional training, fostering a holistic and human-centered perspective within technical education.

The purpose of the proposed tasks was to stimulate students' desire to deepen, develop, apply, and integrate diverse knowledge and skills in practice, incorporating an artistic component into this process. The central theme chosen for the activity involved exploring personality traits and temperaments as psychological characteristics of the individual. Although students already possessed basic psychological knowledge on this topic, it was essential to further develop their understanding of the relationship between psychological concepts and their future professional field.

During the completion of the tasks, the educational and art laboratories of the Cultural and Educational Center (CEC) were actively used. The topic of the activity was "Psychological Modeling: Creating Portraits of Temperaments." The task consisted of several stages and extended over four class sessions.

The first stage was organizational, involving the formation of mini-groups of five to eight students. This step was crucial, as it later enabled the observation of the students' ability to work collaboratively, interact effectively, perform tasks independently, and take responsibility for the team's collective results.

Each group, through a random draw, selected the type of temperament they would study (sanguine, choleric, phlegmatic, or melancholic). At this stage, the groups were tasked with creating a mind map summarizing psychological research related to human temperaments. To ensure diversity, the topics were discussed so that no two groups would repeat the same theme. For example:

– one group analyzed historical perspectives (psychologists who studied temperament and its characteristics);

– another examined the biological foundations of temperament;

– a third explored major theoretical approaches to temperament;

– a fourth analyzed representations of temperament in culture films, cartoons, books, or video games where character temperaments are vividly portrayed.

During the task, the use of digital tools for creating mind maps was prohibited. The maps were drawn manually, using a variety of artistic materials, including pencils, markers, and collage techniques. The activity was designed to activate students' creativity, reveal their artistic potential, and encourage autonomous work without the use of technology. We humorously referred to this assignment as "cave drawings," since some students considered the use of pencils outdated or unnecessary.

At certain stages, this analog format caused difficulties, for instance, in selecting appropriate colors or images, as students had to complete the assignment without digital programs or ChatGPT assistance. Nevertheless, these challenges became an important part of the learning process, promoting reflection, problem-solving, and creative collaboration.

In the final phase, all mind maps were combined into one large composite map with four main branches, each representing one temperament type. Every group presented its work, allowing students to see the studied topic from multiple perspectives and to gain a deeper understanding of its complexity and interconnectedness.

The second stage of the assignment took place in the educational art laboratories of the Cultural and Educational Center, designed as an art-based educational exploration (a guided educational tour) followed by independent research. Building upon their prior knowledge, students were asked to select four paintings that, in their opinion, best represented the type of temperament assigned to their team and reflected the psychological characteristics associated with it. This task was completed independently, without any direct guidance from the instructor.

Students not only chose a painting but also delivered a short presentation, introducing the artist and the history behind the artwork, explaining their interpretation of the image, analyzing the use of color, and justifying their perception of how the artwork corresponds to a specific temperament type. In this way, they transformed the activity into a mini-case study that combined cultural content, elements of personality psychology, and modern digital tools, thus embodying the essence of the STEAM methodology. Each mini-case was presented to the entire group, followed by a discussion and reflection session to analyze the experience and consolidate the learning outcomes.

The third stage of the assignment involved utilizing digital technologies. Each team was asked to confidentially select one painting from among the eight art laboratories of the Center. The content of the chosen painting remained unknown to their opponents but was meant to represent the temperament type assigned to the rival team. The task for each group was to create a list of key descriptive words for the painting they had selected and communicate them to their opponent team. The opposing team then had to generate an image based on those keywords using AI-based image generation tools.

Students were not restricted in their choice of software, though most used freely accessible programs such as DALL·E (by OpenAI), Canva (with AI Generator), and ChatGPT. The teams then displayed their generated images and tried to guess which original painting they represented, identifying the artist, the laboratory where it was located, and discussing whether the image accurately matched the assigned temperament type.

Such assignments not only foster creativity but also develop the ability to describe situations precisely and convey information effectively. During the process, the instructor emphasized that no description is ever completely objective: each speaker interprets reality in their own way, and each listener perceives it differently. Moreover, information transmitted through digital tools is not always reliable, and therefore, it must be verified using multiple sources.

Particular attention was drawn to the fact that answers or materials produced by ChatGPT, used by approximately 87% of the students (according to a survey), are not always accurate or scientifically valid. Hence, genuine research and inquiry-based learning should be grounded in personal investigation, critical analysis, and the use of diverse and credible information sources.

The fourth assignment, titled “Portrait of Temperament: Art Through Science”, combined both individual and group work and incorporated an interactive STEAM-based approach. The individual task involved identifying one’s own personality traits and temperament using a simplified and adapted version of the Eysenck Personality Inventory (EPI; Eysenck & Eysenck, 1963), which consists of 57 questions and measures the personality dimensions of extraversion, introversion, and neuroticism. Based on mathematical calculations and the obtained results, students plotted their coordinates on the axes of introversion-extraversion and emotional stability–instability, locating their position on the chart (Methodical Guidelines for Independent and Individual Work in the Course "Psychology of Personality," 2024, pp. 40-43).

After determining their temperament type, students were asked to produce a visual art image representing their temperament through creative activation. The format of the artwork was not limited: students could use digital tools or traditional artistic media. The task aimed not at drawing a self-portrait but rather at conveying one's inner emotional and psychological state, resulting in a wide variety of interpretations.

A key element of the assignment was confidentiality: artworks were submitted to the instructor through the university's online learning platform and were not revealed to the class until the presentation. During the session, the instructor displayed the works without identifying the authors, and students had to guess who created each image and identify the author's temperament type. This exercise encouraged students to learn more about each other, to better understand the psychological nuances of their peers, and to develop the skill of constructing psychological profiles of their peers.

The proposed active learning technology integrates multiple teaching methods and techniques, including mind mapping, discussion, art-based educational explorations (guided educational tours), debates, creative activation methods, and reflective thinking techniques. Such a diverse implementation of methods and technologies requires a specialized system of assessment. We support the view that for interactive classes to be effective, separate evaluation criteria must be developed for each session, corresponding to the chosen educational technologies, since identical criteria cannot be applied to, for instance, both game-based and training-based technologies.

Considering that the activity was designed according to the STEAM approach, we employed a method that had already demonstrated strong results in previous research: peer assessment. This method involves student-to-student evaluation based on instructor-defined criteria, conducted asynchronously, and serves to enhance the quality and responsibility of students' work (Hrechanovska, 2020, p. 242).

The effectiveness of this method has also been confirmed by international research. Wouter Groeneveld et al. (2020) emphasize that peer assessment is a popular and effective tool for the in-depth evaluation of individual contributions in group projects, noting its positive impact on self-assessment, motivation, and skill development. Their two-year longitudinal study found that "students tend to assess their project more accurately for some, though not all, evaluation criteria after participating in a peer-assessment session; they report higher motivation to continue improving their work, and the correlation between motivation and time spent on the project increases. These findings suggest that peer assessment can have a lasting positive effect on students' reflective abilities and, consequently, on their lifelong learning skills" (Groeneveld et al., 2020).

Of course, the use of Peer Assessment also presents certain challenges, as pointed out by Ashenafi et al. (2015). These researchers, analyzing issues in modern peer evaluation practices, highlight that instructors employing this method should establish interdisciplinary connections, for example, with computer science, which is particularly crucial for classes conducted within the STEAM framework.

The main objective of assessment within the STEAM-based learning model was to delegate the evaluative function to students, while the instructor assumed the role of moderator and facilitator. According to predefined criteria, students evaluated both the performance of competing teams and the individual contributions of members within their own teams. Each task was graded on a five-point scale, and the final score was calculated as the arithmetic mean of all obtained values.

Our previous research (Hrechanovska, 2020, p. 241) demonstrated that "when students evaluate the work of their peers, they apply specific assessment criteria and provide feedback to clarify what needs improvement. Evaluation involves rating scales or various types of explanations and rules." Thus, the peer-assessment method proved to be an effective tool for developing responsibility, analytical thinking, and academic integrity, as it encourages students to engage in the educational process not merely as performers but also as active analysts of learning outcomes. This approach enhances student involvement in learning through the STEAM framework, engaging not only cognitive but also psychological and emotional processes of the individual.

Upon completing the tasks and assessment activities, a reflective thinking discussion was held to analyze the effectiveness of the learning process and the quality of task completion. Students shared their impressions and answered questions from a brief survey. A total of 178 second-year students from various faculties where the elective course "Psychology of Personality" was taught participated in the survey.

The collected data revealed the following results:

To the question "How interesting was the class for you?", 31% responded "very interesting," 45% – "interesting," 18% – "somewhat interesting," and 6% – "not interesting."

In response to "Was the combination of creative tasks and scientific approaches (STEAM) useful?", 49% answered "yes," 41% – "partially," and 10% – "no."

When asked about the challenges they encountered, 82% of respondents reported difficulties completing certain tasks. The main reasons cited were:

– the challenge of performing tasks without relying on computer programs;

– difficulties in collaborating with team members they were not personally close to;

– and peer assessment, which required them to justify their evaluations and engage in face-to-face dialogue with other students.

As the students noted, communicating through chats or social media felt much easier, as it allowed them to express opinions without direct confrontation. They commented that "in chats, you can end the conversation whenever you want and ignore other people's opinions." Such statements reveal that direct interpersonal communication still poses psychological barriers for many students, limiting their ability to express themselves fully. This also highlights a lack of confidence and insufficient preparation for teamwork, particularly in areas such as conflict prevention, acceptance, and resolution.

Despite these challenges, when asked, "Would you like to have more classes like this?", 89% of students responded "yes," while 11% were "unsure." These findings clearly demonstrate a high level of student interest in the continued implementation of STEAM-based learning approaches in higher education.

In the long-term perspective of implementing the STEAM approach into the educational process, we have proposed a series of pilot binary classes within an innovative integrative course titled "Cultural Mathematics" (an original author's development). The course is designed to be team-taught by several instructors and integrates the subjects that constitute the STEAM model. It is built upon interactive (active) teaching technologies that promote both engagement and interdisciplinary synthesis.

The study of this course aims to deepen students' understanding of higher mathematics by interpreting mathematical concepts through the lens of cultural phenomena and their interrelation with technology, science, and engineering. Moreover, it encourages reflection on how these interconnections have shaped human development across various domains. The course seeks to form students' ability to apply mathematical and cultural knowledge in their professional fields, fostering both analytical precision and cultural awareness.

Among the proposed topics currently under development are:

– Culture + Mathematics = ? "The Map of the Discipline Cultural Mathematics" - an introductory interactive lecture;

– The Mystery of DNA Numbers;

– Art, Philosophy, and the Coordinate System: Commonalities and Differences (scalar, vector, and tensor quantities; the Cartesian coordinate system on the plane - analytical geometry);

– The Concept of the Abstract in Cultural Mathematics (abstract linear spaces, abstractionism across art forms - analytical geometry);

– The Phenomenon of the Attractor (differential equations);

– Fibonacci Numbers and the Golden Ratio in World Cultures;

– A Cultural Perspective on the Development of Civilizations Through Mathematical Statistics;

– The Model as an Abstract Representation of Reality (mathematical and artistic modeling);

– The Probable and the Improbable (theory of probability);

– Random Phenomena as Patterns in the Cultural Development of Civilizations (mathematical statistics in experimental analysis).

The proposed course, along with its topics, teaching methods, and the integration of artistic and scientific dimensions, represents a significant step toward embedding the STEAM approach into the educational process of technical universities. It fosters a humanized vision of engineering education, where analytical thinking coexists with creativity, cultural literacy, and reflective understanding of the world.

Conclusions

Within our teaching practice, the implementation of the STEAM approach in work with students particularly through the integration of the educational-artistic laboratories of the Cultural and Educational Center revealed a set of effective educational technologies, including: project-based learning (individual and group projects addressing real-world issues); critical thinking technologies (media analysis, debates, ethical dilemmas); coaching and facilitation (interaction between educational participants through inquiry, support, and intrinsic motivation); interactive (active-learning) technologies (active learner engagement, small-group work, role-playing, situation modeling, guided educational tours); gamification and game-based learning (elements of gamified activities, quests, training games); media education technologies (production of videos, podcasts, social projects); social design technologies (volunteering, charity, environmental initiatives); case-based learning (analysis of real or simulated professional situations); and psychological training technologies.

Nevertheless, combining and applying such diverse teaching methods within the framework of the STEAM approach presents several challenges, which we have identified as follows:

Resistance to traditional systems: Teaching practices are still dominated by traditional forms focused on knowledge reproduction rather than application. Low motivation among some instructors and students is linked to habitual teaching routines. Effective STEAM integration requires thorough instructor preparation (lesson design, evaluation strategies) and student readiness, both intellectually and motivationally.

Insufficient readiness of teaching staff: There is a shortage of professionals capable of integrating cultural-artistic dimension into technical environments and applying interdisciplinary teaching methods. Many students still lack the skills needed for project-based, research-oriented, and creative learning, as well as experience with peer assessment.

Limited material and methodological resources: The absence of fully equipped STEAM laboratories, workshops, and digital platforms hampers the implementation of project-based and integrative learning. Access to quality STEAM methodologies and adapted educational materials for technical higher education remains insufficient.

Challenges of digitalization: Some instructors and students have inadequate digital literacy, and outdated ICT tools are still being used, which do not meet the requirements of modern STEAM environments. The ability to connect artistic and cultural content with digital technologies also remains underdeveloped.

Difficulties in building teamwork and assessing outcomes: Not all students have experience in collaborative or creative group work. When teams form independently, unequal participation often occurs, leading to challenges in applying peer assessment. Moreover, assessing soft skills, creativity, and innovation remains a complex task.

Cultural barriers to the artistic component: The cultural and artistic dimensions of STEAM are often undervalued in the training of future technical professionals and perceived as “additional” or secondary, which reduces motivation to integrate them meaningfully into the curriculum.

Hence, our work represents an attempt to implement and integrate the STEAM approach into the training process for future technical specialists. While the proposed methodology may not be universally applicable across all technical universities or fully meet expectations regarding its implementation, it nonetheless demonstrates a viable and innovative direction. If the focus were solely on the STEM model, fewer challenges of integration would emerge; at the same time, integrating the cultural-artistic dimension into the technical domain requires not only addressing the above challenges but also achieving broader societal recognition of the importance and necessity of the STEAM approach in shaping the engineers of the future.

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2.2. Designing the activities of Pre-service mathematics teachers using Maple to prepare them for the implementation of STEM education

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***Abstract**. The article is devoted to analyzing and justifying the importance of integrating computer algebra systems (CAS), particularly Maple, into teacher education for pre-service mathematics teachers. The key aspects of utilizing such systems for developing STEM competencies, enhancing research skills, integrating interdisciplinary knowledge, and creating an innovative learning environment are considered. The document highlights the role of Maple in transforming traditional mathematics education into a digital and STEM-oriented paradigm, emphasizing practical approaches to designing educational activities. This study aims to explore the role of Maple-based computer tools in the context of training pre-service mathematics teachers to implement STEM education while studying a discrete mathematics course. The research methods used in the article include theoretical analysis, systematization, and generalization of data from scientific, methodological, and specialized literature. The article addresses the training of pre-service mathematics teachers to implement STEM education by designing their professional activities using the Maple computer mathematics system. The feasibility of integrating Maple into the professional training of teachers as a means of forming digital, research, and interdisciplinary competencies is substantiated. A project activity model is proposed, based on the principles of the STEM approach and utilizing Maple as a tool for modeling, visualization, and analytical processing of mathematical problems. The use of Maple in the training of mathematics teachers promotes the integration of knowledge from related disciplines, characteristic of STEM, and ensures the readiness of future teachers to utilize digital technologies in organizing collaborative learning and project work within the STEM education framework. This aligns with modern trends in mathematics education, which place special emphasis on innovative methods and technologies.*

***Keywords**: STEM education, Maple, pre-service mathematics teacher, digital competence, digital literacy, modeling, project activity.*

DOI: 10.31110/STEM-CaUk-2.2

Introduction

STEM education (Science, Technology, Engineering, and Mathematics) is one of the most important priorities in global education policy, aimed at training qualified personnel for an innovative economy. Global trends clearly indicate an increase in demand for STEM specialists, with forecasts predicting a 20% rise in job opportunities in these areas by 2030. Countries with a high level of development are actively investing in the development of STEM competencies, recognizing that this is a key factor in national competitiveness.

In Ukraine, according to the National Strategy for the Development of Education, the development of STEM competencies is identified as a key area. This involves the formation of students' not only in-depth knowledge of natural sciences and mathematics, but also the development of critical thinking, problem-solving skills, innovative thinking, and interdisciplinary interaction. Traditional education often falls short in preparing young people for the realities of the 21st century, where the ability to apply knowledge in practice and work effectively in a team is crucial. STEM education is designed to overcome these gaps by offering an integrated approach to learning that reflects the complexity and interconnectedness of the real world.

This necessitates adapting teachers to the implementation of STEM education, which requires them not only to possess deep subject knowledge but also to be able to integrate technology into the educational process.

One of the most important aspects of high-quality teacher training is the creation of an effective and dynamic learning environment. Such an environment should rely on interactive models and multimedia resources that enhance student engagement and motivation. Research confirms that the use of dynamic systems enables the development of innovative methodological resources, significantly enhancing the motivation and competence of future teachers for STEM integration (Yurchenko et al., 2022).

In the context of modernizing school education and transitioning to STEM-oriented approaches, the need arises for high-quality training of pre-service mathematics teachers to integrate interdisciplinary learning, research methods, and digital technologies into the educational process (Marchisio et al., 2022). Modern educational challenges require not only a deep understanding of mathematical content but also the ability to utilize modern digital tools, particularly computational mathematics systems, to create models, analyze data, and visualize results. One such powerful tool is Maple, which serves as an interactive platform for mathematical computations and is widely used in higher education to support research and teaching activities.

An analysis of scientific sources on the introduction of digital technologies into the process of professional training of pre-service mathematics teachers (Yunchyk & Fedoniuk, 2019; Cardoso-Espinosa et al., 2021; Gudmundsdottir & Hatlevik, 2018) shows that digital technologies contribute not only to increasing the speed of learning material but also to the formation of deep conceptual understanding among students through visualization and modeling processes, which previously required lengthy analytical calculations (Kovalova et al., 2022).

To ensure high-quality instruction, various computer mathematical systems have been developed, which are divided into several classes. The first class includes systems that work with traditional methods of writing mathematical formulas and are primarily focused on solving complex computational problems and modeling processes, such as Maple, MATLAB, Mathematica, and Maxima. They provide a flexible environment for solving diverse mathematical problems, including discrete structures (Engelbrecht & Borba, 2024). Another class includes dynamic mathematics programs such as GeoGebra and Cabri, which focus on visualization and interactive study of mathematical objects. They are especially useful in the initial stages of training, when clarity and visual perception play an important role (Osypova & Tatochenko, 2021).

Canadian practice in integrating Computer Algebra Systems (CAS), particularly Maple, into STEM teacher training is an important component of modern pedagogical education. Research conducted among 302 Canadian mathematicians showed that the use of CAS in teaching promotes the visualization of mathematical concepts and stimulates students' research activities (Buteau et al., 2013).

Universities such as the University of Waterloo actively incorporate Maple into their curricula, particularly in linear algebra courses, enabling students to gain a deeper understanding of abstract mathematical concepts (Corless et al., 2023).

Additionally, platforms like Möbius provide interactive STEM learning using powerful mathematical engines, which contribute to the development of key competencies in future teachers (Möbius, https://www.digitaled.com/mobius/).

These initiatives demonstrate how integrating CAS into pedagogical practice can significantly improve teacher preparation and support the advancement of STEM education.

Maple (Maple, www.maplesoft.com), as part of the computer mathematics systems, stands out among others due to its extensive mathematical functions for analysis and powerful visualization tools, which make it a versatile tool for teaching discrete mathematics to future bachelor's students. Practical tests and research conducted by us in the process of teaching discrete mathematics to pre-service mathematics teachers demonstrate its effectiveness in improving the quality of specialist training (Lukashova et al., 2022).

Integrating computer algebra systems (CAS) such as Maple into pre-service mathematics teacher education is a highly relevant and promising pedagogical direction.

Research objective. To explore the role of the Maple computer software tools in the context of preparing pre-service mathematics teachers for the implementation of STEM education during the study of the discrete mathematics course.

Research methods. Theoretical analysis, systematization, and generalization of data from scientific, methodological, and specialized literature.

Research Results

Designing activities for future teachers using the Maple software involves creating educational and practical situations in which students utilize digital tools to solve interdisciplinary tasks. This approach enables them to develop not only subject-specific skills but also key competencies, such as critical thinking, analytical skills, creativity, and teamwork. Maple offers numerous opportunities for implementing STEM-related tasks, including graphing, solving equations, studying functions, and modeling physical processes or economic situations mathematically. Such tasks can cover several subject areas, including physics, computer science, and biology, which align with the principles of STEM education.

Maple, like other dynamic mathematical software systems, contributes to the development of several key competencies necessary for a modern teacher, as illustrated in Figure 1.

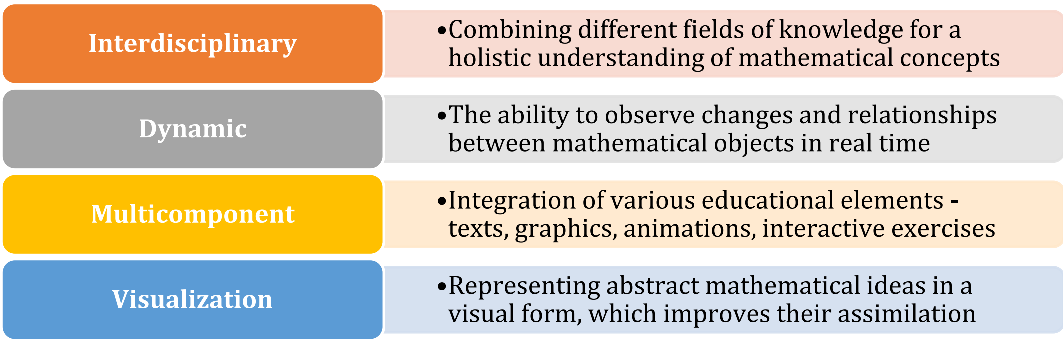

Figure 1. Key competencies developed with Maple

This approach provides a deeper understanding of the material and develops practical skills that are necessary for the successful implementation of STEM approaches in school education.

Maple, as a powerful computer algebra system, offers unique opportunities for the development of key competencies among pre-service mathematics teachers, which are integral to the successful implementation of STEM education. It enables students not only to study theory but also to actively apply it in practice, thereby fostering the development of in-depth research skills, critical thinking, and a creative approach to solving mathematical problems (see Fig. 2).

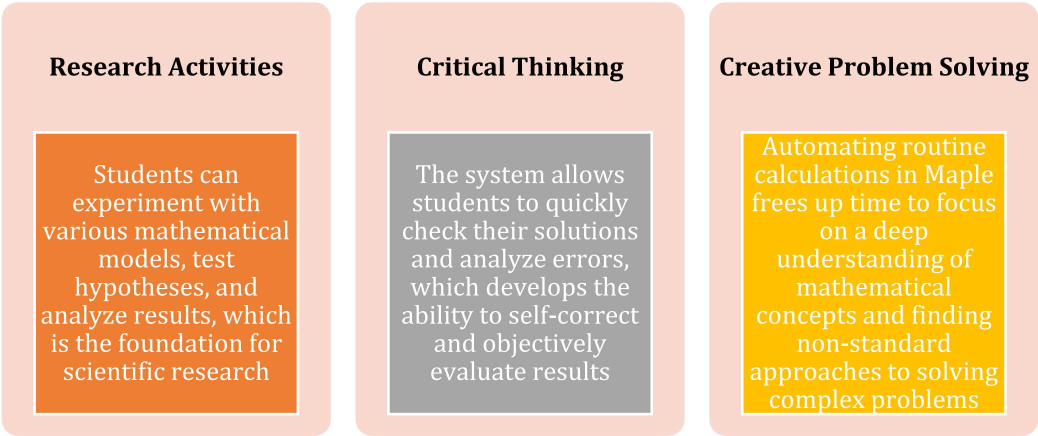

Figure 2. Maple’s role in teacher competency development

These aspects are critically important for training teachers who will not only impart knowledge but also inspire students to engage in their own independent exploration and discovery.

In the modern educational environment, the importance of information and digital technologies in the professional training of pre-service mathematics teachers continues to increase annually. The use of computer-based mathematical systems has become an integral part of the educational process, as such tools significantly improve the quality of training, making it more interactive and focused on practical results. At the same time, computer support fully aligns with modern pedagogical standards and existing requirements for specialist training, as it expands the possibilities of pedagogical activity and creates new incentives for creative and experimental work by both students and teachers.

The implementation of STEM education in Ukrainian schools presents several significant challenges for mathematics teachers (Yurchenko et al., 2022). One of the primary issues is the inadequate level of interdisciplinary training among teachers (Namukasa et al., 2022). Many mathematics teachers lack sufficient experience or knowledge in related fields such as physics, chemistry, biology, or engineering, which makes it difficult to integrate these disciplines into a unified educational process. Another challenge lies in the difficulty of integrating abstract mathematics with real-world STEM tasks. Students often perceive mathematics as a set of formulas and theorems detached from real life, without recognizing its practical applications (Zhou & Li, 2021). The teacher's task is to demonstrate how mathematical models help solve specific problems in everyday life, science, and engineering.

Additionally, limited access to modern educational technologies and software, as well as insufficient instructional time for developing practical modeling and simulation skills, pose significant challenges. Addressing these challenges requires a systemic approach to teacher education supported by appropriate tools and resources (see Fig. 3).

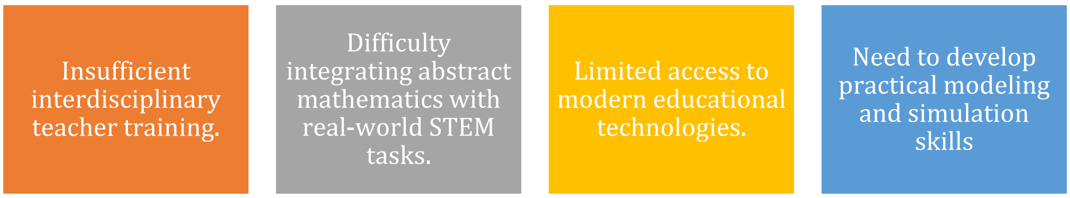

Figure 3. STEM implementation challenges for teachers

The Maple computer algebra system is a powerful and multifunctional tool that can significantly transform the approach to teaching mathematics within STEM-oriented instruction. It provides unique opportunities for training future teachers, allowing them not only to deepen their own mathematical knowledge but also to learn how to effectively utilize modern technologies for modeling and visualizing complex processes.

Maple has powerful computational capabilities that cover symbolic, numerical, and graphical calculations. This enables users to work with algebraic expressions, differential equations, integrals, linear algebra, and many other areas of mathematics with high accuracy and speed. Maple's interactive environment facilitates modeling, simulation, and data visualization, which is critically important for understanding abstract concepts in physics, engineering, and other natural sciences.

In addition, Maple offers specialized packages that are designed to solve problems in physics, engineering, statistics, and chemistry, making it an indispensable tool for interdisciplinary STEM projects. Programming support in Maple enables teachers to create custom applications and interactive models, providing flexibility in developing unique educational materials and tasks. Thanks to Maple, future teachers will be able not only to teach mathematics but also to integrate it into real-world contexts, demonstrating its applications and significance in modern scientific and technological developments.

Maple opens up a wide range of opportunities for integrating mathematics into various STEM disciplines through practical, visual examples. These cases demonstrate how abstract mathematical concepts gain concrete meaning when applied to real-world problems (see Fig. 4).

Physics

- Flight trajectory modeling: analysis of projectile motion taking into account air resistance, allowing visualization of the influence of various parameters on its path.
- Calculation of speed and acceleration: interactive study of kinematics.

Engineering

- Analysis of structural deformations: use of differential equations to calculate stresses and strains in beams, bridges, trusses.
- Optimization of engine parameters: determination of optimal values for maximum efficiency.

Chemistry

- Visualization of chemical reaction kinetics: interactive study of reaction rates and the influence of concentration and temperature.
- Optimization of synthesis conditions: finding the best conditions for maximum product yield.

Statistics

- Processing of real data: analysis of environmental data, sociological surveys, construction of regression models for forecasting.
- Statistical analysis of climate change: studying trends and anomalies.

Biology

- Forecasting population growth: application of logistic models to analyze the dynamics of animal or microorganism populations.
- Modeling of disease spread: simulation of epidemic processes.

Figure 4. Opportunities for STEM integration with Maple

To effectively prepare mathematics teachers to implement STEM education using Maple, a comprehensive methodology has been proposed, which includes several key stages (see Fig. 5). This methodology is based on project-based learning and the integration of theoretical knowledge with practical applications (Kieran, 2019).

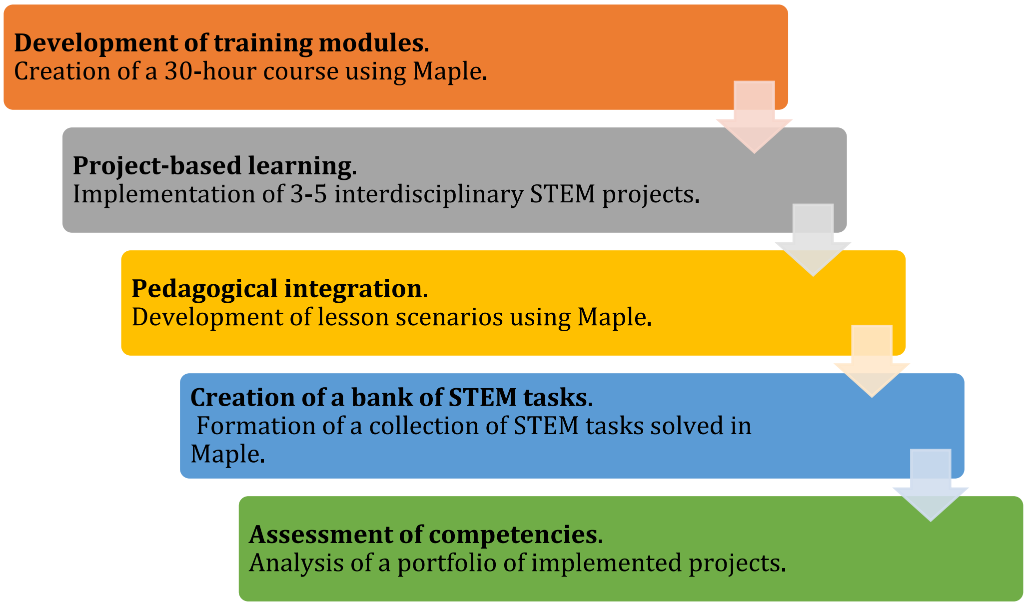

Figure 5. Methodology for STEM training with Maple

The first step is to develop structured learning modules. It is recommended to create an intensive 30-hour course on using Maple, which will cover the program's main functions and their applications in a STEM context.

The second stage focuses on project-based learning. Teachers should complete 3–5 interdisciplinary projects that demonstrate the application of mathematics and Maple to real-world problems in physics, engineering, biology, or chemistry. These projects should be complex enough to require a deep understanding of the material and a creative, analytical approach.

The third stage of pedagogical integration involves the development of lesson scenarios where Maple is used as the primary tool for visualization, modeling, and problem-solving. Teachers should not only learn to use the program but also to effectively implement it within the educational process.

The fourth stage involves creating a bank of STEM problems solved in Maple. This will become a valuable resource for pre-service teachers, encouraging the exchange of experiences.

The final stage involves assessing competencies, which is achieved through a portfolio of implemented projects and a demonstration of the ability to integrate Maple into the educational process.

This approach will ensure deep mastery of the material and confident application of Maple in professional activities.

The implementation of this program for training pre-service mathematics teachers using Maple is expected to yield several significant positive outcomes and benefits, impacting both the teaching staff and the quality of student education.

First of all, teachers are expected to significantly increase their confidence in their ability to effectively integrate STEM approaches into the educational process by approximately 25–30%. This will be achieved by deepening their knowledge in interdisciplinary aspects and mastering modern technological tools such as Maple. This, in turn, will have a positive impact on students' academic performance, as their performance in mathematics and natural sciences is predicted to improve by 10–15%, given that learning becomes more visual, interactive, and practically oriented.

In addition, such training will contribute to the development of key skills in schoolchildren, in particular critical thinking and the ability to solve complex problems, which are the basis of STEM competencies (see Fig. 6). Students' interest in studying STEM subjects will increase significantly as they observe the practical application of the knowledge they have gained. In the long term, this will lead to the formation of an innovative environment in educational institutions, where teachers and students actively use modern technologies for research and creativity, preparing for the challenges of the future.

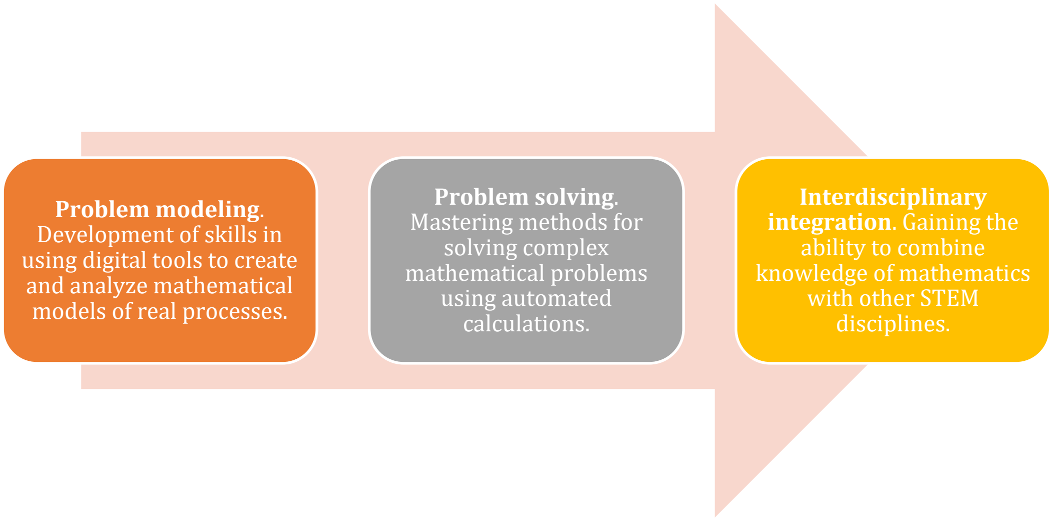

Figure 6. Effects of program implementation

During training, it was found that students who actively used Maple in project activities demonstrated a higher level of digital and professional competence. They are better oriented in the structure of STEM tasks, able to create interactive models, and effectively apply their knowledge in new educational contexts. This is achieved because the content of the presented model is closely related to the formation of methodological readiness of pre-service mathematics teachers for teaching STEM-oriented topics and the integration of digital technologies into educational practice through the following means:

1. Familiarization with the functionality of Maple;
2. Integration of Maple into mathematics courses through educational projects;
3. Development of interdisciplinary STEM tasks using Maple;
4. Independent design by students of educational cases and scenarios for mathematics lessons integrated with natural or technical disciplines;
5. Reflection and analysis of the effectiveness of the tools used.

One of the key advantages of using Maple in training pre-service mathematics teachers is its ability to stimulate the integration of knowledge from related disciplines. This feature is characteristic of STEM education, which requires specialists to take an integrated approach to problem-solving. Maple allows the modeling of phenomena from physics, engineering, economics, and other sciences using mathematical tools that make learning more visual and applied. This ensures the readiness of future teachers to:

– Use digital technologies: effectively use software for demonstrating, analyzing, and modeling various processes;
– Organize collaborative learning: create conditions for students to work as a team on projects that require the integration of knowledge from different subjects;
– Manage project work: supervise student projects aimed at solving real problems using an interdisciplinary approach.

Thus, Maple becomes a tool that not only deepens mathematical knowledge but also develops a broad worldview and the practical skills necessary for implementing innovative educational approaches.

To better understand the benefits of Maple in the context of STEM teacher training, it is useful to conduct a comparative analysis with other popular dynamic mathematics systems (see Table 1). While each system has its own unique capabilities, Maple stands out for its power in symbolic computations and its wide range of functionality.

Thus, Maple is a versatile tool that combines the capabilities of deep mathematical analysis with interactive learning tools, making it an ideal choice for training STEM teachers.

The effective implementation of Maple in the training of pre-service mathematics teachers requires the careful design of educational tasks and methodological materials. These materials should be designed in such a way as to maximize the use of computer technologies, promote the development of interdisciplinary knowledge, and support the formation of STEM competencies:

Table 1. Comparative analysis of Maple with other dynamic mathematical systems in the context of teacher training for STEM education

Characteristic	Maple	GeoGebra	Wolfram Alpha
System Type	Computer Algebra System (CAS)	Dynamic Mathematical System	Computational Knowledge Base
Symbolic Computing	High level	Limited	High level
Numerical Computing	High level	High-level	High level
Graphic Capabilities	Powerful 2D/3D	Powerful 2D/3D (interactive)	Limited (static)
Programming	Embedded language	Scripting	Unavailable
Interdisciplinarity	High (physics, engineering)	Intermediate	High (broad spectrum of knowledge)
Educational Use	Deep research, analysis	Visualization, interactive models	Quick answers, verification

1) computer modeling tasks**:** development of scenarios that involve building mathematical models of real-world phenomena (e.g., population dynamics, motion of bodies) using Maple;

2) problem-oriented cases**:** creation of tasks that require the use of Maple to solve atypical, complex problems that go beyond the scope of standard textbooks;

3) methodological recommendations**:** development of detailed instructions and manuals for students on the use of Maple functionality in pedagogical practice;

4) project work**:** organization of individual and group projects where students use Maple to research interdisciplinary topics.

The key principle should be an interactive and research-based approach that allows students not only to absorb information but also to actively create new knowledge and gain practical experience. This meets the need to transform traditional education toward a digital and STEM-oriented paradigm.

The integration of software, particularly computer algebra systems (CAS) such as Maple, into the training of pre-service mathematics teachers is not only desirable but also a necessary condition for the formation of highly qualified specialists ready for the challenges of STEM education. Maple offers powerful tools for developing research, analytical, and interdisciplinary competencies, which form the foundation of the modern educational process. This enables future teachers to move beyond routine calculations toward a deeper conceptual understanding.

Using Maple in mathematics teacher training facilitates the integration of knowledge from related disciplines, which is characteristic of STEM, and ensures that future teachers are ready to utilize digital technologies in organizing collaborative learning and project work.

Discrete mathematics occupies a special place in the education of pre-service mathematics teachers in the Educational and Professional Program Secondary Education (Physics, Mathematics), at the second (master's) level of higher education, Sumy State Pedagogical University named after A.S. Makarenko (2020). Its content consists of clearly defined structure sets, graphs, combinations, and networks, which differ in their characteristics of discreteness (Lukashova et al., 2022). In the pedagogical context, it is essential that pre-service mathematics teachers possess the skills to visualize and analyze these structures, which enables a deeper understanding of the essence of discrete structures and the mechanisms of their functioning (Lukashova et al., 2022).

Among the sections of discrete mathematics, graph theory is defined as STEM-oriented. Graph theory, as a crucial area of discrete mathematics, has numerous applications in computer science, logistics, bioinformatics, sociology, and other fields, which underscores the need for its in-depth study using modern tools.

Maple has built-in packages that allow users to create, explore, and analyze graphs of various types (directed, undirected, weighted, trees, etc.). In particular, using the GraphTheory package, users can perform operations on graphs, determine their main characteristics (degrees of vertices, number of edges, presence of cycles, connectivity components), perform path searches, and calculate various metric properties (diameter, eccentricity, center, radius, etc.).

The advantage of Maple is its ability to visualize graphs effectively, which significantly facilitates the understanding of abstract concepts and structures. For example, when solving problems to find a minimum spanning tree (Prim's or Kruskal's algorithm), students can observe the step-by-step formation of the tree. Similarly, when studying depth-first search (DFS) or breadth-first search (BFS) algorithms, the implementation in Maple allows users to track the order of visiting vertices and the dynamics of constructing a traversal tree.

Using Maple increases students' motivation to study graph theory and promotes the development of algorithmic thinking, programming skills, and the analysis and synthesis of mathematical models. Additionally, the system facilitates complex calculations with large datasets, significantly reducing time and enabling students to focus on the theoretical analysis of the problem.

Thus, the integration of Maple into the study of graph theory contributes to a deeper mastery of educational material, the development of students' applied competencies, and the formation of a modern scientific worldview. This is especially important in the preparation of future mathematics, computer science, and applied mathematics teachers, for whom the ability to work with computer mathematical systems is a crucial component of their professional activity.

Graph visualization is a central tool for representing discrete structures in Maple. The system supports the construction of graphs as objects consisting of nodes and edges, which can be directed or undirected, depending on the educational tasks. This allows not only for the visual representation of structures but also for their detailed analysis. The Maple GraphTheory package also contains algorithmic tools for determining graph properties, such as vertex degrees, cycles, and connectivity, which are critically important for understanding the topology and functional characteristics of graphs (Maple. URL: www.maplesoft.com/). The relationship between analytical information, calculated using built-in functions, and its graphical display is one of Maple's key advantages. This contributes to the development of a purposeful perception of mathematical objects in students and provides flexible opportunities for research and interpretation of their properties in a visual mode.

One of the main problems of graph theory, typically considered in standard discrete mathematics courses, is the problem of establishing graph isomorphism, which illustrates the algebraic characteristics of graphs. Isomorphism is a key property of a graph, allowing us to determine whether different diagrams (graph drawings) represent the same graph or distinct graphs. This enables further questions about representing a graph in its simplest form or in a way that makes it convenient to establish its properties.

Graphs $G_1=(V_1,E_1)$ and $G_2=(V_2,E_2)$ are called isomorphic if there exists a one-to-one mapping ϕ: $V_1 \rightarrow V_2$ that preserves vertex adjacency, i.e., an edge $\{\phi(u), \phi(v)\} \in E_2$ if and only if $\{u, v\} \in E_1$. The fact that graphs G_1 and G_2 are isomorphic is written $G_1 \cong G_2$, and the mapping ϕ is called the isomorphism of G_1 onto G_2.

Directly establishing the isomorphism of two graphs "manually" and finding correspondences between their vertices is a rather complicated task. First, it is necessary to check whether the number of vertices and edges in the graphs coincide, and secondly, whether the number of vertices of each degree in both graphs coincides. If at least one of these parameters does not coincide, the graphs are not isomorphic. Otherwise, it is necessary to check whether the isomorphism condition is fulfilled for all correspondences between the vertices of graphs G_1 and G_2 (considering that vertex degrees are preserved during isomorphism).

Let us consider an example of such a task.

Example 1. Prove that the graphs shown in the figure are isomorphic. Solve the problem using the definitions, adjacency, and incidence matrices of the graphs (see Fig. 7).

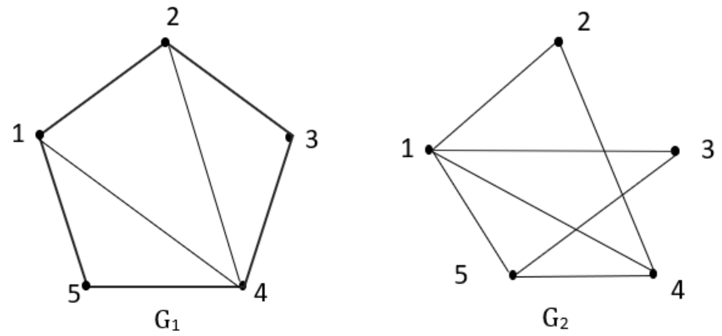

Figure 7. Graph diagrams G_1 and G_2

Solution. It is obvious that the given graphs have the same number of vertices and edges. In addition, in both graphs there is one vertex of degree 4 and two vertices of degrees 2 and 3. Considering that in isomorphism the degrees of the vertices do not change (i.e., vertices of one degree in the first graph correspond to vertices of the same degree in the other graph), the following correspondences between the vertices of the graphs are possible G_1 and G_2:

$$\phi_1 = \binom{12345}{54213},\ \phi_2 = \binom{12345}{45213},\ \phi_3 = \binom{12345}{54321},\ \phi_4 = \binom{12345}{45312},$$

where the first line contains the vertex numbers of the graph G_1, and the second line contains the vertex numbers of the graph G_2.

Let us check whether the correspondence ϕ_1 is an isomorphism of graphs, i.e., let us check whether the condition is fulfilled: $\{\phi_1(u), \phi_1(v)\} \in E_2 \Leftrightarrow \{u, v\} \in E_1$. Let us list all edges of the graph G_1 and find their images under the mapping ϕ_1 :

e_i	{1,2}	{1,4}	{1,5}	{2,3}	{2,4}	{3,4}	{4,5}
$\phi_1(e_i)$	{5,4}	{5,1}	{5,3}	{4,2}	{4,1}	{2,1}	{1,3}

Since the images of all edges belong to the graph G_2, the mapping ϕ_1 is an isomorphism, i.e., cap G sub 1 approximately equal to cap G sub 2, which was to be proved.

Another way to establish an isomorphism is to use adjacency or incidence matrices. This method allows us to reduce the study of graph properties to the study of the properties of their corresponding matrices (adjacency and incidence, respectively).

Recall that the adjacency matrix of a simple graph with n vertices is the matrix $A = \langle a_{ij} \rangle$ of nth order, in which

$$a_{ij} = \begin{cases} 1, \text{if vertices } i \text{ and } j \text{ are adjacent,} \\ 0, \text{otherwise.} \end{cases}$$

Accordingly, the incidence matrix of a graph with *n* vertices and *m* edges is called the matrix B=$\langle b_{ij} \rangle$ of dimension $n \times m$ in which

$$b_{ij} = \begin{cases} 1, \text{if vertex } i \text{ and edge } j \text{ are incident,} \\ 0, \text{otherwise.} \end{cases}$$

Graphs $\mathrm{G_1 = (V_1, E_1)}$ and $\mathrm{G_2 = (V_2, E_2)}$ are isomorphic if and only if they have the same number of vertices and the adjacency matrices of these graphs are similar, i.e. there exists a nondegenerate matrix *Q* such that $A(G_2) = Q \cdot A(G_1) \cdot Q^{-1}$, where $A(G_1)$ and $A(G_2)$ are the adjacency matrices of graphs G_1 and G_2. Or the adjacency matrix $A(G_1)$ of graph G_1 can be obtained from the adjacency matrix $A(G_2)$ of graph G_2 by simultaneous permutations of the same rows and columns.

Graphs $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$ are isomorphic if and only if they have the same number of vertices and edges, and the incidence matrix $I(G_1)$ of graph G_1 can be obtained from the incidence matrix $I(G_2)$ of graph G_2 by arbitrary permutations of rows and columns.

Let us now prove the isomorphism of graphs G_1 and G_2using their adjacency matrices. It should be noted that establishing isomorphism by proving the similarity of adjacency matrices is a rather cumbersome problem, which is considered in linear algebra. Therefore, it is better to use the second method, which reduces to a simple permutation of the rows and columns of the matrix.

Let us write the adjacency matrix of the graph G_1:

$$A(G_1) = \begin{pmatrix} 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{pmatrix}.$$

Let's rearrange the first and fourth rows and, respectively, the columns of this matrix, and then the second and fifth rows and, respectively, the columns:

$$A(G_1) = \begin{pmatrix} 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{pmatrix} \sim \begin{pmatrix} 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{pmatrix} \sim$$

$$\sim \begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{pmatrix} = A(G_2).$$

Since, as a result of such transformations, we obtain the adjacency matrix $A(G_2)$ of the graph G_2, then $G_1 \cong G_2$.

The solution to this problem using graph incidence matrices is similar. However, unlike the previous method, arbitrary permutations of the rows and columns of the matrices are used.

Let us now solve the specified problem using the computer mathematics system Maple.

To do this, first connect the GraphTheory module (command > with(GraphTheory):).

We will define each graph with a list of edges and construct graph diagrams in Maple. To do this, we use the commands

> G := Graph({{a, c}, {a, e}, {b, c}, {b, d}, {b, e}, {d, e}}) and > DrawGraph(G) respectively (see Fig. 8).

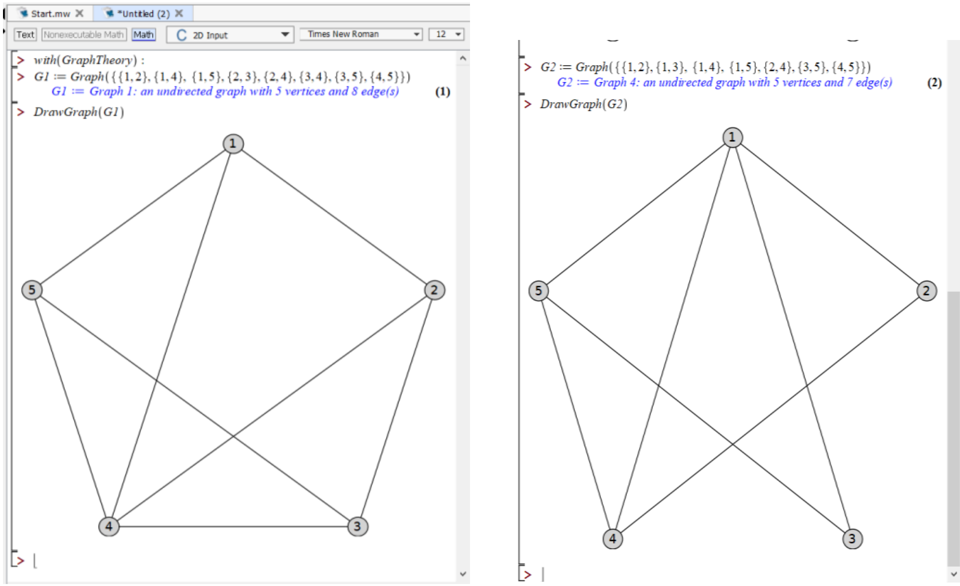

Figure 8. Graph diagrams G_1 and G_2 from Example 1 in Maple

Let's find out if the graphs are isomorphic using the command

> IsIsomorphic(G1, G2, 'mp').

The answer to the question is given in Figure 9 – true, that is, the graphs are isomorphic.

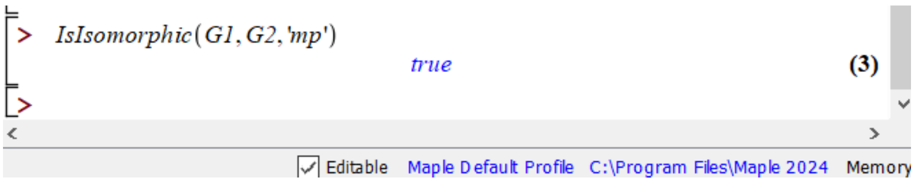

Figure 9. Defining graph isomorphism in Maple

Let's determine the number of vertices of graphs that correspond to each other under isomorphism (command > mp) (see Fig. 10).

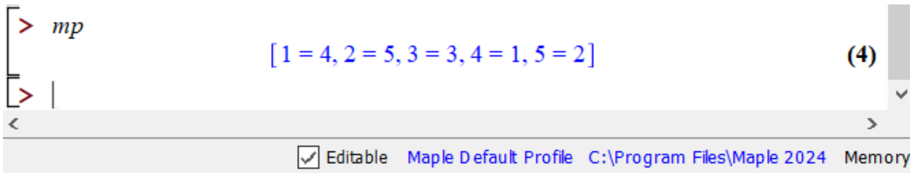

Figure 10. Establishing correspondence between graph vertices under isomorphism in Maple

Thus, Maple allows us not only to determine whether graphs are isomorphic but also to identify a specific correspondence between vertices under the isomorphism. In this case, the system gives a correspondence that corresponds to the vertex substitution $\phi_4 = \binom{12345}{45312}$ given above.

Another way to find out whether graphs are isomorphic is to examine their adjacency matrices. The construction of matrices can also be done in Maple with the command

>A := AdjacencyMatrix(G).

To determine the similarity of adjacency matrices, we will use the LinearAlgebra module and connect it with the command > LinearAlgebra:. Next, we will use the command > IsSimilar(A1, A2) to determine the similarity of the matrices. The answer is true - the matrices are similar, therefore, the graphs are isomorphic (see Fig. 11).

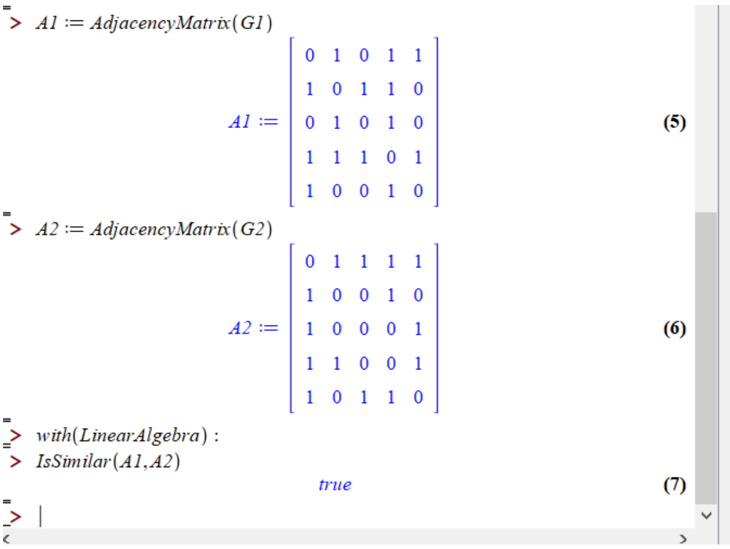

Figure 11. Establishing matrix similarity in Maple

Note that the LinearAlgebra module allows you to determine the similarity of matrices in another way: by finding their eigenvalues. From the course of linear algebra, it is known that matrices are similar if and only if they have the same characteristic roots. Figure 12 shows the result of applying the > eigenvals(A) command, which allows you to find the characteristic roots of a matrix, to the adjacency matrices of given graphs. As shown in Figure 13, the roots are the same; therefore, the matrices are similar, and the corresponding graphs are isomorphic.

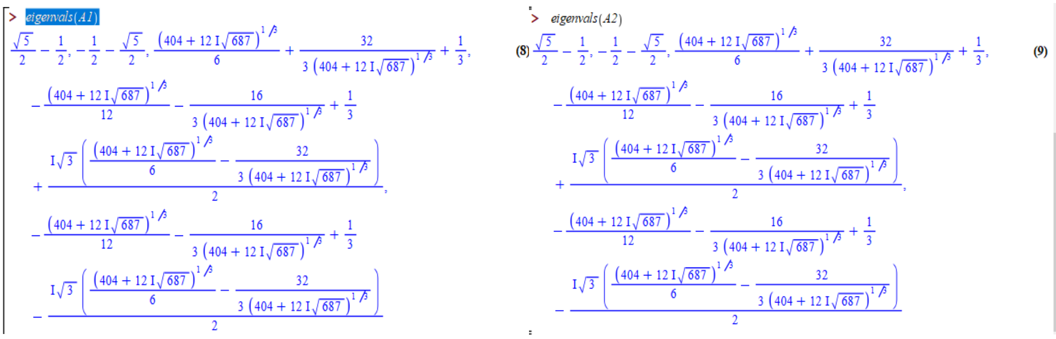

Figure 12. Result of determining characteristic roots of adjacency matrices in Maple

Let's consider another example of using the Maple system to establish graph isomorphism.

Example 2. Find out whether the graph *G*, given by the list of edges E = {{a, c}, {a, e}, {b, c}, {b, d}, {b, e}}, is self-complementary.

Solution. Recall that a graph is called self-complementary if it is isomorphic to its complement. Accordingly, the complement of the graph *G*=(*V*,*E*) is the graph G_1, which has the same set of vertices as the graph *G*, and any two vertices of G_1 are adjacent if and only if they are not adjacent in *G*.

Give the graph *G* and find its complement G_1 (command >G1:= GraphComplement(G)).

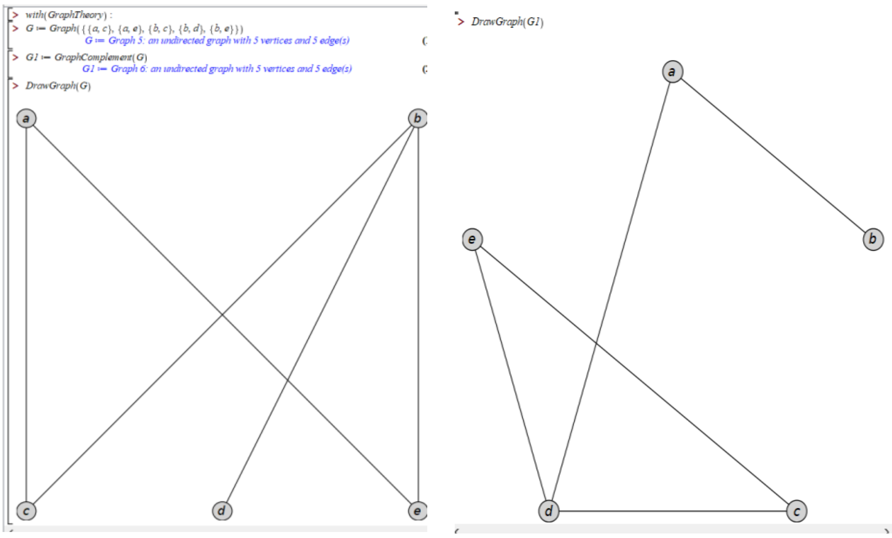

Figure 13. Graph construction and its addition in Maple

Let's determine whether these graphs are isomorphic (theoretically, this is possible, given that the number of edges and vertices in both graphs is the same) (see Fig. 14).

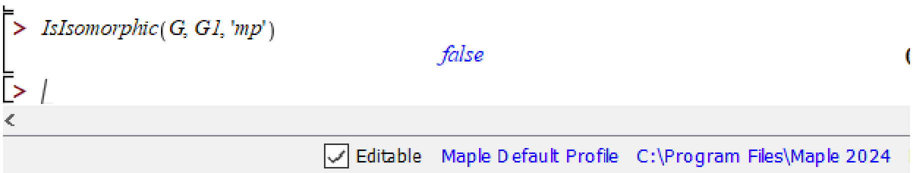

Figure 14. Establishing a graph isomorphism and its complement

Therefore, the graph and its complement are not isomorphic, so this graph is not self-complementary.

One of the key advantages of Maple is the ability to create interactive and dynamic graph visualizations. The system supports real-time modification of graph parameters and displays the effects of these changes, providing students with a clear understanding of internal interactions within the structure. The use of animation enhances clarity when demonstrating algorithms for working with graphs, such as breadth-first or depth-first traversals, cycle detection, or solving routing problems (Kovalova et al., 2022). This enables the creation of experimental training modules, where students can conduct research, test hypotheses, and observe the behavior of mathematical structures in a dynamic manner. Such an approach activates students' creative potential and promotes deeper assimilation of the material.

Along with visualization, Maple provides a comprehensive analytical toolkit for studying the structural characteristics of graphs. The system enables users to calculate various parameters, including vertex degrees, path lengths, and cycles, which are key indicators in graph theory. It also supports the identification of specific types of subgraphs, such as trees or covers, which is useful in teaching discrete mathematics and its applied aspects. Of particular importance is the use of functions for finding optimal routes, minimum covers, and other optimization problems, which allows for the consideration of both static and applied aspects of graph research (Maple, www.maplesoft.com). These capabilities are fundamental for developing practical skills essential for the profession of a mathematics teacher.

Building on the theoretical framework described above, the next section presents empirical evidence from a pilot study conducted with pre-service mathematics teachers. A pilot study was conducted at Sumy State Pedagogical University, enrolling 22 pre-service mathematics teachers in a discrete mathematics course from 2023 to 2025. Participants were divided into a control group (2023-2024, 14 students) (traditional instruction without Maple and without STEM-oriented emphasis) and an experimental group (2024-2025, 8 students) (instruction integrating Maple to implement STEM). In the experimental instruction, Maple was used for modeling, visualization, and solving discrete mathematics problems, as well as for implementing 3–5 project-based tasks that combined mathematics with physics, computer science, or biology to simulate STEM-oriented scenarios. Additionally, Maple was integrated into practical sessions of the discrete mathematics course, allowing students to create interactive models and explore algorithms such as graph traversals and isomorphism.

Comparing the grades of students in both groups for the discrete mathematics course, preliminary conclusions indicate that the experimental group demonstrated significantly higher results. In particular, the average score for solving complex interdisciplinary tasks was 18% higher than in the control group. Surveys were also conducted among the experimental group participants to determine whether the use of Maple and STEM-oriented practices increased their engagement during the course. Eighty-five percent of participants reported confidence in using Maple to solve mathematical problems. Surveys also indicated an increased interest in the course, attributed to its interactive visualization and project-based activities. Furthermore, participants in the experimental group effectively applied mathematical concepts in the contexts of physics and computer science, demonstrating enhanced interdisciplinary STEM thinking skills.

These results suggest that integrating Maple into the training of pre-service mathematics teachers promotes the development of digital, research, and interdisciplinary competencies, fosters critical thinking and creativity, and improves practical problem-solving skills in future STEM educators.

In light of the above, the following recommendations can be formulated to further improve the educational process.

1. Include specialized courses on the use of Maple (or other CAS) for solving applied problems in various STEM disciplines.

2. Develop interactive textbooks and online resources containing examples of using Maple to demonstrate mathematical concepts.

3. Encourage students to carry out research projects using CAS, which will develop their research competencies.

4. Organize training sessions and seminars for teachers on the methodology of integrating Maple into various sections of mathematics and related disciplines.

5. Create interdisciplinary projects that combine mathematics, physics, engineering, and technology, leveraging the capabilities of Maple.

The implementation of these recommendations will contribute to the further transformation of mathematics education in Ukraine, making it more innovative, practically oriented, and aligned with the modern global requirements of STEM education.

Conclusions

Using Maple in the training of pre-service mathematics teachers is an effective tool for developing the key competencies necessary for implementing STEM education. This approach contributes to the modernization of pedagogical education, enriching it with digital tools and fostering readiness for interdisciplinary integration in the educational process. Further research can focus on developing original training modules and methodological recommendations for teachers in higher education institutions specializing in pedagogy.

Designing activities for pre-service mathematics teachers using Maple is an extremely promising direction for modernizing Ukrainian education and adapting it to the requirements of the 21st century. Maple has proven to be an effective tool, allowing not only the deepening of mathematical knowledge but also its integration into the interdisciplinary context of STEM education. A comprehensive training approach, which includes theoretical instruction, project-based learning, and pedagogical integration, ensures the development of all necessary competencies in teachers for the successful implementation of STEM approaches in schools.

Using the Maple computer mathematics system to solve graph theory problems allows the implementation of several didactic objectives: first, to consolidate knowledge of the basic concepts and algorithms used in graph theory; second, to accelerate the solution of complex problems and verify and compare manually obtained results; third, to review material from other mathematical courses (in this case, linear algebra); and finally, to effectively conduct students' research activities in mathematics or other sciences using Maple tools.

In the training of pre-service mathematics teachers, special attention is given to the development of digital competencies, which are essential for the effective use of Maple and similar systems in professional contexts. These competencies encompass not only technical skills in working with CAS, but also an understanding of the methodology behind its application in teaching discrete mathematics, organizing the educational process, and moderating students' learning activities. Teachers should not only master these tools but also act as facilitators who help students maximize the benefits of working with computer tools.

The successful implementation of this program offers significant benefits, including increased professional confidence among teachers, improved academic performance among students, the development of critical thinking and problem-solving skills, and heightened overall interest in STEM disciplines.

In view of this, further prospects include expanding the training program at the national level, covering as many pedagogical universities and postgraduate education institutes as possible. It is also important to conduct long-term studies on the impact of such training on student achievement and their readiness for future careers in STEM fields. This will enable continuous improvement of methods and ensure high-quality education, which is crucial for the innovative development of society.

Designing activities for pre-service mathematics teachers using software, particularly computer algebra systems (CAS) such as Maple, is a relevant direction for preparing teachers to implement STEM education. The use of Maple, like other dynamic mathematical systems, contributes to the development of key competencies in future teachers, particularly the ability to utilize digital technologies for modeling, solving mathematical problems, and integrating interdisciplinary knowledge, which forms the foundation of the STEM approach.

One important aspect of such training is the creation of an effective learning environment based on interactive models and the use of multimedia resources. For example, studies show that dynamic systems, such as GeoGebra AR, can create innovative methodological resources that enhance the motivation and competence of future teachers within STEM, through the interdisciplinary, dynamic, and multi-component nature of the educational process.

Maple, as a computer algebra system, enables students to develop research, critical thinking, and creative problem-solving skills, which are essential for STEM education. It also supports the automation of routine calculations, freeing up time for a deeper understanding of content and the development of pedagogical competencies.

The use of Maple in the training of mathematics teachers promotes the integration of knowledge from related disciplines, characteristic of STEM, and ensures the readiness of future teachers to utilize digital technologies for organizing collaborative learning and project work. This aligns with modern trends in mathematics education, which place special emphasis on innovative methods and technologies.

Thus, the design of activities for pre-service mathematics teachers using Maple should include the creation of educational tasks and methodological materials that stimulate the use of computer technologies in solving complex problems, the development of interdisciplinary knowledge, and the formation of STEM competencies through interactive and research-based approaches. This corresponds to the need to transform traditional education towards a digital and STEM-oriented paradigm.

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Chapter 3

STEM-ORIENTED TRAINING OF FUTURE TEACHERS

3.1. Prospects for the Use of STEM Education in the Professional Training of Future Primary School Teachers

Galina Rozlutska, Svitlana Hirniak, Yaroslav Petryna

***Abstract**. The study examines the feasibility of integrating STEM education (science, technology, engineering, and mathematics) into the training system for future primary school teachers. The relevance of the research is determined by the need to develop new competencies among teachers that meet the challenges of the technological era and the goals of the New Ukrainian School (NUS) educational reform. The paper analyzes scientific approaches to defining STEM competence of a primary school teacher, whose structure comprises cognitive, operational, motivational, and reflective components, as well as organizational and methodological conditions for its development in higher education institutions, including the creation of a STEM-oriented learning environment, implementation of integrated courses, and engagement in project-based learning.*

The empirical study was conducted at Uzhhorod National University and included a two-stage survey of 45 pre-service primary school teachers (27 bachelor's and 18 master's students) before and after the introduction of STEM elements into the curriculum. The results demonstrated a statistically significant improvement in students' readiness to implement innovative teaching methods, with the average stem readiness index increasing from 59% to 69%. Positive changes were observed in knowledge, motivation, and self-efficacy, with the greatest progress shown by students with lower initial levels. A moderately positive correlation was found between pre- and post-test results ($r \approx 0.46$), indicating a partial dependence on prior preparation and the effectiveness of the pedagogical intervention.

It was concluded that STEM-oriented training constitutes a promising pathway toward the modernization of teacher education. Integrating STEM technologies into university courses, equipping laboratories, and engaging students in project and research activities enhances the quality of professional training, fosters innovative thinking and interdisciplinary collaboration skills, and readiness to utilize contemporary educational tools and methods. The findings

DOI: 10.31110/STEM-CaUk-3.1

may serve as a methodological foundation for designing educational programs that prepare teachers of a new generation.

***Keywords**: STEM education, teacher training, primary school, STEM competence, innovative teaching technologies, pedagogical experiment.*

Introduction

Global challenges of recent years, including epidemics, natural disasters, and military conflicts, have accelerated the digitalization of educational services. During the war, Ukrainian education shifted to distance and blended learning formats. The adoption of an integrated learning approach has significantly transformed the requirements for knowledge and competencies among all participants in the educational process. Innovative competence has become a professional necessity for a new generation of teachers capable of working effectively in a rapidly changing world, marked by technological advancements and social shifts. Consequently, STEM education (Science, Technology, Engineering, Mathematics) has gained increasing recognition in many countries.

In realizing the potential of STEM education, the role of the primary school teacher is crucial, as it is at this level that learners first encounter scientific and technological ways of understanding the world. Therefore, modern teachers must not only possess subject knowledge but also be able to integrate different fields, apply innovative teaching methods, and use advanced technologies in instruction. This creates the need for change in the system of professional teacher training.

This study substantiates the prospects for using STEM education in the preparation of future primary school teachers, taking into account both international experience and the realities of Ukrainian higher education. It also presents the results of an empirical study on the effectiveness of STEM-oriented learning among students of pedagogical specialities.

Analysis of current research

In contemporary academic literature, STEM education is viewed as a modern educational paradigm grounded in the integration of natural sciences, mathematics, and technology (including information and communication technologies) to address pressing issues of educational development. The core idea of STEM education is to strengthen the scientific and technological dimension of learning, create conditions for developing students' creativity, and enhance teachers' professional competence (Zorochkina & Zdir, 2024). Research emphasizes that STEM education aims to develop a holistic system of knowledge, skills, and modes of thinking, while also fostering research abilities, an engineering approach to problem-solving, critical thinking, and creativity.

The STEM (Science, Technology, Engineering, Mathematics) concept is becoming increasingly widespread worldwide, as the integration of scientific and technical disciplines with creative elements substantially improves the quality of professional training (Molnar, 2023). STEM education represents a forward-looking model for curriculum design, one that integrates various disciplines in an interdisciplinary manner. Its principal goal is to modernize educational content in line with contemporary demands, strengthening the scientific and technical orientation of instruction, fostering youth creativity, and improving teachers' professional competence. STEM-based learning develops competent, creative, and innovation-oriented individuals ready to face the challenges of modern society. The key competencies of the New Ukrainian School (NUS) align naturally with the structure of STEM education, forming a foundation for learners' successful personal and professional growth (Zorochkina & Zdir, 2024).

Accordingly, a modern teacher must possess STEM competence, a dynamic combination of knowledge, skills, values, and personal qualities that enable innovative work and the effective implementation of STEM methodologies in the educational process. Zorochkina and Zdir (2024) define the structure of STEM competence for future primary school teachers as comprising cognitive, operational, personal-motivational, and reflective components. Developing these components requires a deliberately structured educational process in higher education institutions. Effective approaches include engaging students in practical and research activities, completing STEM projects, mastering key STEM concepts within professional methodology courses or specialized disciplines, using active and technology-based teaching methods, and creating a STEM-oriented learning environment.

An essential condition for the successful integration of STEM components into teacher education is the modernization of the organizational and methodological foundations of the instructional process. As O. Kuzenko (2021) emphasizes, updating the methodological support for teacher preparation should lead to the emergence of an "educator of a new generation," whose defining characteristic is the ability to apply innovative pedagogical technologies. A contemporary teacher must be free from outdated stereotypes and capable of creating a learning environment that fosters both effective instruction and the development of a child's creative potential. The content, forms, and methods of teacher training should be oriented toward cultivating the ability to overcome innovation barriers, define pedagogical goals, achieve them through the use of modern educational technologies, and continuously engage in professional growth (Kuzenko, 2021).

In Ukraine, this issue has particular significance in light of the New Ukrainian School reform and the country's integration into the European educational sphere, both of which impose higher standards on teacher education. As O. Akimova (2024) notes, the teacher of the New Ukrainian School must simultaneously act as a tutor, facilitator, and researcher, while being proficient in information and communication technologies and foreign languages.

Within the broader development of STEM education, the experience of teacher preparation in Canada offers particularly instructive examples. According to Johnson, Walton, and Breiner (2020), the implementation of STEM education in teacher training falls under provincial jurisdiction, yet a shared vision of strategic priorities has been established at the national level. The Council of Ministers of Education, Canada (CMEC), identifies STEM education as one of the main priorities for advancing educational programs across the country.

This has translated into tangible policy reforms. For instance, in Ontario, a revised Science & Technology curriculum introduced in 2022 mandates the study of coding fundamentals and engineering design beginning in Grade 1 (Ontario Ministry of Education, 2022). Such measures reflect a global trend toward modernizing teacher education to meet the demands of a STEM-oriented society.

The Canadian higher education sector in pedagogy actively experiments with institutional models of STEM training. Specialized programs have been introduced, for example, the B.Ed. (Secondary) The STEM one-year program at Thompson Rivers University prepares teachers of integrated natural sciences and mathematics with a strong emphasis on engineering and technology (Thompson Rivers University, 2022).

Another approach involves creating STEM-oriented learning environments within traditional teacher education programs. For instance, the Faculty of Education at the University of Ottawa established the edstudiO laboratory, equipped with 3D printers, robotics kits, and other innovative tools. In this space, pre-service teachers learn to design lessons based on experimentation and play (University of Ottawa, 2024). As a result, graduates of Canadian teacher preparation programs demonstrate a high level of readiness to integrate modern technologies and online resources into their professional practice, a model that can serve as a benchmark for Ukrainian teacher education under current conditions.

Equally noteworthy is Canada's experience in post-graduate teacher education, where a well-developed system of continuous professional development for STEM educators has been established. This system ranges from regular training sessions organized by local school boards to nationwide initiatives such as the Let's Talk Science program, which offers webinars, summer institutes, and online courses aimed at enhancing teachers' STEM-related skills (Innovation, Science and Economic Development Canada, 2021).

Importantly, participation in high-quality STEM training has a measurable effect on teacher motivation. According to Allen and Sims (2017), the likelihood of STEM teachers remaining in the profession increases by 160% among those who engage in ongoing professional development. Implementing similar mechanisms in Ukraine through mentorship systems, partnerships between schools and universities, and flexible professional learning formats could ensure both sustainability and effectiveness in advancing STEM education.

Thus, the Canadian experience of teacher preparation provides valuable insights that can be adapted to the Ukrainian educational landscape through a three-tiered model of STEM implementation:

(1) National level – recognition of STEM education as a strategic priority for educational development;

(2) Regional level – institutionalized integration of STEM into school and teacher education programs;

(3) Institutional level – combining theoretical understanding of STEM with the practical development of STEM competencies in an interdisciplinary learning environment.

Ukrainian scholars also acknowledge the importance of incorporating STEM education into teacher training. H. Klimashevska (2024) demonstrates the positive impact of STEM education on the development of innovative thinking and creative abilities in future teachers. She recommends that pedagogical universities, in alignment with Ukraine's integration into the European educational space, enrich their teacher training curricula with specialized methodologies that foster creativity in both classroom learning and independent work, as well as teaching practice. Similarly, O. Karpenko (2024) emphasizes the need to introduce compulsory courses on STEM education covering its principles, technologies, and tools within higher pedagogical institutions and professional development programs. This, in her view, would strengthen teachers' readiness to apply innovative instructional technologies in practice.

A. Diachenko and Kh.-M. Popyuk (2021) investigated teacher preparation for teaching the integrated course Design and Technologies in primary school. They concluded that such preparation is inherently multifaceted and includes mastering pedagogical technologies of learner-centered and competence-based instruction, acquiring technical and technological knowledge and skills, learning new teaching methods (such as game-based and project-based learning), and developing the ability to integrate design and visual arts concepts into other educational fields. Importantly, as the authors emphasize, design education is inherently interdisciplinary. It synthesizes technology and art. Therefore, future teachers must master the fundamentals of design (including composition, color theory, and related principles) to apply them effectively across various subjects.

Overall, the analysis of Ukrainian academic sources demonstrates that integrating STEM education into the professional preparation of primary school teachers is a multifaceted task. First, there is a need to clearly define the content of teachers' STEM competence and the pathways for its development during university training. Second, it is necessary to modernize curricula and academic programs by introducing specialized STEM modules, project-based and research tasks, and elective courses that equip students with practical skills in applying interdisciplinary approaches. Third, creating an appropriate instructional and methodological environment is crucial. This involves establishing the necessary material and technical infrastructure (laboratories, equipment, and software), as well as developing textbooks and methodological guidelines to help instructors integrate STEM technologies into pedagogical disciplines (Molnar, 2023).

A strong base of innovative experience is already taking shape: numerous collections and manuals on implementing STEM education have been published, while electronic resources and online platforms are being actively introduced. These enable students and instructors to use modern tools such as web-based services and virtual laboratories (Molnar, 2023). Pedagogical universities should demonstrate institutional readiness and commitment to these innovations by conducting interactive sessions focused on developing STEM-related skills among future teachers (Molnar, 2023).

Leading international studies underline that the effective implementation of STEM education in teacher preparation requires a systematic and comprehensive approach. An analysis of publications from 2019 to 2024 reveals a global trend toward integrating STEM disciplines into teacher education curricula, establishing STEM laboratories and project modules, and developing students' interdisciplinary competencies (Thanh et al., 2025). For example, in China, the government has initiated numerous Teacher Professional Development (TPD) programs that emphasize interdisciplinarity, curriculum renewal, and the enhancement of teachers' technological proficiency. Reviews of these projects indicate that Chinese TPD initiatives focus on creating integrated courses, expanding the practical component of instruction, and promoting the use of modern ICT tools. Many of these training programs have gradually adopted blended or fully online formats (Rehman et al., 2025). This aligns with broader global initiatives: in both the United States and Europe, it is widely acknowledged that preparing next-generation teachers must extend beyond discrete subject instruction to include practical STEM projects, the development of critical thinking, and collaborative practices (Thanh et al., 2025).

A vital component of teacher education programs is the inclusion of project-based activities. Researchers have observed that working on real-world projects that incorporate science, technology, engineering, and mathematics (STEM) significantly enhances pre-service teachers' motivation and confidence in their own abilities. A study conducted in Turkey found that participation in STEM-design courses where students develop a project from concept to implementation substantially improved pre-service teachers' self-efficacy in the STEM field (Elmali & Kiyici, 2025). However, novice teachers often encounter difficulties distinguishing between the engineering and technological components of their projects, highlighting the need for additional instruction focused on these specific elements of STEM.

A similar emphasis on project-based work was observed in Israel, where groups of students collaboratively designed interdisciplinary STEM lessons that integrated two or three subject areas simultaneously. Analysis of these modules revealed that pre-service teachers tended to concentrate on individual tasks while neglecting the development of collaborative skills (Anabousy & Daher, 2022). Such findings highlight the need for providing targeted instructional support during project-based learning, including direct facilitation and mentoring that aim to strengthen teamwork and creative thinking abilities. Consequently, many international programs include STEM laboratories and makerspaces where students can test their projects under faculty supervision, fostering creativity and innovation-oriented competencies.

In global STEM pedagogy, considerable attention is given to developing specialized STEM competencies among future teachers, a comprehensive combination of knowledge, skills, and values that enables effective integration of STEM methods into the educational process. International programs employ active learning techniques such as practical workshops, case-based learning, online laboratories, and project or research assignments implemented in real or simulated learning settings (Rehman et al., 2025; Anabousy & Daher, 2022). This approach cultivates critical thinking, collaboration skills, and proficiency in using modern technological tools (P21 Partnership, 2019; Elmali & Kiyici, 2025). For instance, partners in Israeli programs emphasize that projects should include research and analytical stages, promote data-based reasoning, and foster scientific modes of inquiry and evidence-based decision-making.

Engaging students in project-based and interdisciplinary activities increases their motivation and confidence (Elmali & Kiyici, 2025). At the same time, major differences between international and Ukrainian contexts lie in scale and resource availability. While in other countries STEM laboratories and continuous teacher development programs are often supported by government initiatives or the technology industry, Ukrainian efforts are more commonly implemented through research projects and faculty-level initiatives within individual universities.

Therefore, it can be argued that both international programs and Ukrainian practice are increasingly focused on integrating courses and developing STEM competencies. In both contexts, the project-based methodology serves as a central mode of learning, encompassing instructional case studies, laboratory experiments, and interdisciplinary educational initiatives. In Ukraine, particular emphasis is placed on advancing the New Ukrainian School (NUS) reform and aligning teacher education with European standards. The innovative teacher is expected to act as a facilitator and tutor, equipped with proficiency in ICT and 21st-century skills.

International research confirms that such competencies, critical thinking, digital literacy, and creativity form the foundation of STEM education and are integral to educational development strategies in the United States, China, the European Union, and other regions (Rehman et al., 2025; Elmali & Kiyici, 2025). Globally, the need to modernize teacher preparation through practice-oriented STEM courses, interdisciplinary tasks, and continuous professional development supported by digital technologies, online training, and remote laboratories is widely recognized.

What unites Ukraine with international systems is the focus on project- and research-based learning, integrated courses, and the cultivation of innovative thinking among future teachers. The main differences lie in the scope of support and the specific instruments employed. Abroad, these efforts are typically embedded in national strategies and supported through well-funded STEM centers. In Ukraine, innovative laboratories and courses are often implemented as local initiatives within individual universities or faculties.

Modern approaches to teacher education aim to prepare future educators for life in a digital society characterized by rapid technological transformation, a goal reflected in numerous international strategies and programs. In the European Union, the Digital Education Action Plan 2021–2027 identifies the modernization of teacher preparation as a key priority for promoting digital and STEM skills among school students. The strategy highlights a shift in the teacher's role from a transmitter of knowledge to a tutor and mentor capable of organizing learning through digital tools and project-based methods (European Commission, 2023, p. 15).

The digitalization of education requires future teachers to develop strong ICT competencies. As shown by recent international studies, nearly all countries have incorporated the enhancement of teachers' digital skills into their national education strategies. Ukraine has also adopted a Digital Education Strategy, and the New Ukrainian School reform promotes IT integration as a guiding trend in teaching and learning (Ministry of Education and Science of Ukraine, 2021).

At the same time, global data reveal a significant increase in attention to STEM education at the primary level: the number of scholarly publications on STEM for younger students has increased substantially. Key topics include embedding STEM into school curricula, developing children's abilities for self-directed learning and inquiry, and encouraging the use of advanced technologies such as robotics and virtual laboratories. These developments respond to the demands of the 21st century, as societies increasingly require not isolated subject knowledge but a holistic understanding, the ability to apply mathematics and science to real-world problems, think creatively, and work collaboratively (Elmali & Kiyici, 2025).

For Ukraine, global educational challenges are being addressed through the New Ukrainian School (NUS) reform, which aims to foster creative and technologically literate citizens. The key competencies outlined in NUS research skills, critical thinking, and ICT literacy closely align with the core ideas of STEM education. According to Ukrainian experts, a modern primary school teacher must be not only a transmitter of knowledge but also a facilitator and mentor capable of organizing project-based learning and critically evaluating information. The ongoing digitalization of education, in particular, requires teachers to be ready for continuous professional growth and to regularly update their technological skills.

An analysis of scholarly sources confirms that STEM education represents a promising direction for improving teacher preparation, as it makes learning more engaging, technologically advanced, and connected to real-life applications. Pre-service teachers who participate in STEM-oriented activities during their training develop critical thinking, teamwork, problem-solving skills, and familiarity with innovative teaching methods (Molnar, 2023; Zorochkina & Zdir, 2024). These outcomes enhance their professional competence and readiness to implement innovations in schools. At the same time, existing research underscores the need for additional empirical studies to determine the optimal models and conditions for integrating STEM components into university teacher education curricula.

Strengthening the role of STEM education in higher pedagogical education corresponds with global sustainable development and 21st-century learning strategies. It broadens opportunities for integrating innovative instructional methods into primary classrooms and prepares teachers to act as creators of new ideas and technological solutions in their professional practice. Examining leading international practices helps justify national innovations such as fostering teachers' STEM competence, advancing project- and research-based learning, and updating teacher education content in line with modern professional standards.

The significance of this study lies in its applied orientation. It offers empirically grounded insights for enhancing the preparation of future teachers within the framework of STEM education. Unlike purely theoretical investigations, the findings of this research possess direct practical value and can serve as a tool for modernizing teacher education in higher pedagogical institutions. The presented results and conclusions form a scientific and methodological foundation for preparing a new type of professional and educator-researcher, innovator, and mentor capable of effectively implementing STEM principles in professional practice for the benefit of future generations.

The *purpose* of this study is to provide theoretical substantiation and experimental modeling of approaches to implementing STEM education in the professional preparation of future primary school teachers. This objective entails analyzing scientific and methodological literature on the issue, identifying the structural components of teachers' STEM competence, developing organizational and methodological approaches to fostering this competence during training, and evaluating the effectiveness of integrating STEM elements into the preparation of pre-service primary school teachers based on empirical evidence. The rationale behind this goal lies in the societal demand for educators who can apply integrative and innovative methods in teaching young learners, as well as in the presence of state-level support for STEM education development, which necessitates corresponding transformations in the content and methods of teacher education.

Research Design

To test the hypothesis regarding the positive impact of STEM-oriented learning on the professional preparation of future teachers, a two-stage survey was conducted among students enrolled in the Primary Education program (specialty A3 in Ukraine). The study employed a quasi-experimental pretest–posttest design that monitored changes in key indicators, using a pretest-posttest design without a control group.

The sample consisted of 45 students from the Primary Education program at Uzhhorod National University: 27 bachelor's students (fourth year) and 18 master's students (first year of the master's program). The choice of this sample aimed to capture different levels of teacher training bachelor's students who had already acquired foundational pedagogical knowledge and master's students who possessed practical teaching experience and a higher motivation toward innovation.

The primary data collection method was a specially designed questionnaire aimed at assessing STEM competence and related indicators among pre-service teachers. The questionnaire comprised two parts: a knowledge test and an attitudinal self-assessment scale.

The first section consisted of 15 test items that evaluated basic STEM knowledge in natural sciences, mathematical concepts, and technologies, all adapted to the primary education level. The second section included 20 Likert-scale statements (ranging from 1 – "strongly disagree" to 5 – "strongly agree") that measured participants' self-perceived readiness and attitudes toward implementing STEM methodologies in the classroom. These statements addressed aspects such as confidence in STEM knowledge, interest in integrated instruction, readiness to apply experimental methods in teaching, and the ability to use modern technological learning tools.

Based on participants' responses to the Likert-scale items, an integrated indicator, the STEM Readiness Index, was calculated to represent the overall level of competence (expressed as a percentage ranging from 0 to 100%). The index was computed by averaging the normalized results of the knowledge test (in %) and the mean score from the self-assessment scale (converted to %). Thus, the index combined both objective knowledge and subjective readiness or motivation.

At the first stage (September 2024), all participants completed an initial survey (pre-test) prior to studying elective courses that incorporated STEM modules. Baseline results, including test scores and self-assessment data, were recorded and used to calculate the initial STEM Readiness Index (Stage 1).

During the semester, STEM elements were purposefully integrated into the learning process of the experimental group. Bachelor's students, as part of the course Methods of Teaching Natural Sciences, completed a mini-project in engineering design, constructing simple devices from available materials. Master's students, meanwhile, implemented segments of STEM lessons during their teaching practice in schools using lesson plans they had developed themselves.

Additionally, four thematic workshops were organized for all participants:

- Robotics and its applications in primary education;
- Use of computer simulations for modeling natural phenomena;
- Methodology of conducting STEM field trips;
- Design of integrated STEM lessons.

Students also worked in a university laboratory equipped with computers and STEM kits (including construction and experimental materials) and gained access to an online platform containing methodological resources. At the end of the semester (second stage, December 2024), a post-test was administered using the same questionnaire.

The collected data were processed using descriptive statistics and correlation analysis. The significance of changes between the two stages was evaluated using the paired Student's t-test for dependent samples, while the relationship between pre-test and post-test results was examined using Pearson's correlation coefficient (r). Statistical analyses were performed in IBM SPSS Statistics, with a significance level set at $p < 0.05$.

Research Results

The initial survey revealed that students' readiness to implement STEM education was at a moderate level, with a mean STEM Readiness Index of 59.1% at Stage 1. This indicates that participants possessed basic knowledge and a general interest in innovation, though many still lacked confidence in their ability to apply STEM methodologies in practice. Specifically, only 22% of respondents at the beginning of the academic year fully agreed with the statement *"I am capable of organizing an integrated STEM lesson in primary school"*, while approximately 40% expressed uncertainty about their ability to do so. Fewer than one-third of the students achieved high scores on the knowledge test (over 70% correct answers). As expected, master's students demonstrated slightly higher results than bachelor's students: 65.0% versus 55.0% according to the index (see Table 1).

At Stage 2 (after the integration of STEM components into the curriculum), a clear positive trend was observed. The mean overall STEM Readiness Index increased to 69.0%, representing a 9.9 percentage point gain compared to the baseline. Improvements were recorded in 82% of participants, with 60% showing substantial growth (over 10 points) and 22% exhibiting moderate progress (5–10 points). Only a few isolated cases showed no improvement or a slight decline, likely due to subjective factors such as fatigue at the end of the semester. Statistically, the difference in mean scores between the two stages was significant ($p < 0.001$, paired t-test), confirming the effectiveness of the implemented pedagogical interventions.

Table 1. Average STEM Readiness Scores of Students at the Beginning and End of the Experiment (as a Percentage of the Maximum Score)

Student Group	*N*	*Stage 1 (M ± SD)*	*Stage 2 (M ± SD)*	*Δ (points)*
Bachelor's students (4th year)	27	55.3 ± 9.5	67.1 ± 10.4	+11.8
Master's students (1st year)	18	64.7 ± 7.8	72.2 ± 9.0	+7.5
Total sample	45	59.1 ± 10.0	69.0 ± 12.0	+9.9

The obtained results indicate a statistically reliable increase in both knowledge and self-perceived readiness to use STEM approaches in teaching. This supports the hypothesis that targeted integration of STEM-oriented activities and environments within teacher education programs enhances future educators' motivation, confidence, and competence in applying innovative instructional practices.

As shown in Table 1, at Stage 1, master's students demonstrated a higher average level of STEM readiness (≈approximately 65%) compared to bachelor's students (≈approximately 55%). This result was expected, as the master's students had already completed their initial pedagogical training and some possessed prior teaching experience. However, following the experimental instruction, the gap between the groups decreased: the bachelor's students showed substantial improvement (+11.8 points), while the master's students' increase was smaller (+7.5 points). This suggests that the integration of STEM elements, particularly for those with a lower initial level of preparedness, produces a "leveling effect." At the same time, master's students also showed measurable progress, indicating that STEM-oriented learning yields additional positive outcomes even for participants with higher baseline competencies.

To gain a deeper understanding of these changes, a scatterplot was constructed to illustrate the relationship between individual students' results at both stages (Figure 1). On the horizontal axis, the pre-test STEM Readiness Index (Stage 1) values are plotted, while the vertical axis represents post-test values (Stage 2) for each of the 45 participants. The dashed line indicates the bisector $y = x$, which corresponds to an unchanged score, allowing for a clear visual representation of individual progress relative to the baseline.

Most data points in Figure 1 are located above the "y = x" line, which indicates an overall increase in performance. It is also evident that students with relatively low initial scores (on the left side of the graph) showed the greatest improvement; their points are positioned well above the diagonal, whereas those who began with high scores remained approximately at the same strong level, with their points clustering near the diagonal.

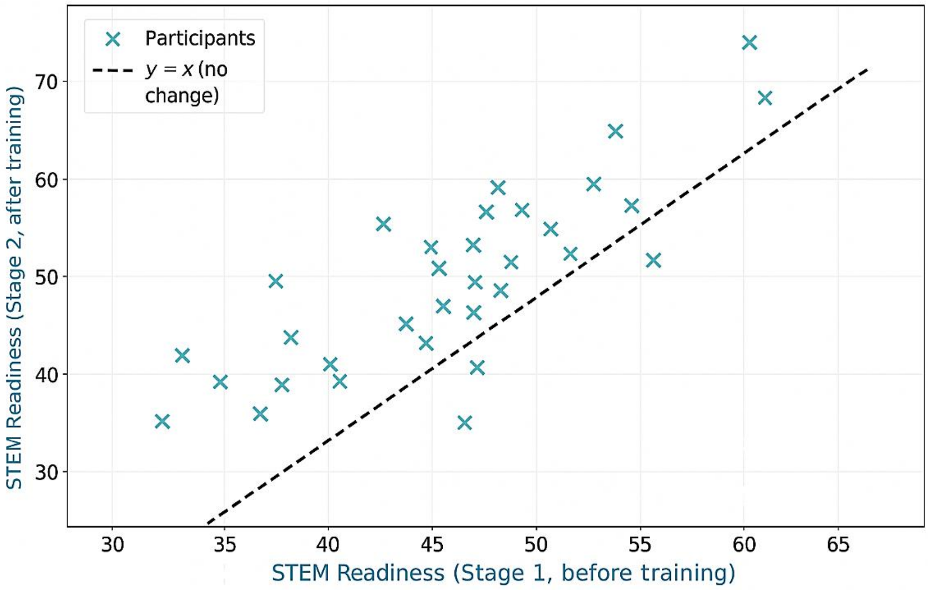

Figure 1. Relationship between students' STEM readiness before and after training

Statistical analysis revealed a moderately positive correlation between the results at the two stages, with a Pearson's correlation coefficient of $r = 0.46$ ($p < 0.01$). This suggests a moderate tendency: students who initially demonstrated stronger STEM readiness tended to maintain relatively high results after training. However, the correlation value is not very high, indicating a partial reorganization of the group under the influence of the intervention; those who started at lower levels made significant progress. Hence, the initial level of preparedness only partially determined the final outcomes.

A closer examination of the questionnaire subscales revealed that the greatest progress was made in motivation and self-confidence indicators. For instance, the proportion of respondents who fully agreed with the statement "I am excited about the idea of teaching children through the STEM approach" increased from 36% at the beginning to 67% after training. Self-efficacy also rose markedly: over 60% of students at Stage 2 rated their ability to design an integrated lesson as high, compared to only about 20% before the intervention. In the test section, performance improved notably on practical tasks. For example, while fewer than half of respondents initially identified the function of a sensor in an educational STEM kit correctly, after hands-on sessions, 80% succeeded. These findings confirm the effectiveness of practice-oriented methods: students not only assimilated theoretical concepts but also learned to use concrete technological tools, such as assembling simple electrical circuits and working with Lego Education kits.

Correlation Analysis. In addition to the previously noted relationship between baseline and final indicators, we analyzed the internal structure of STEM competence components. The correlation between knowledge test scores and self-assessed readiness at Stage 1 was $r = 0.34$ ($p < 0.05$), indicating a weak-to-moderate relationship: not all students who performed well on the test rated their readiness to implement STEM approaches highly, and vice versa. This suggests that some respondents possessed theoretical knowledge but lacked confidence in its practical application, while others were highly motivated toward innovation but had not yet acquired sufficient mastery of the subject.

After the intervention, this correlation strengthened to $r = 0.58$ ($p < 0.01$), approaching a moderately high level. This can be interpreted as follows: through practical experience, students gained a more accurate awareness of their abilities. Those who achieved strong knowledge results generally also felt more confident, and vice versa. In other words, by the end of the experiment, the components of STEM competence had become more coherent and interrelated.

These findings align with broader trends reported in the literature. Specifically, our experiment confirmed that the intentional integration of STEM elements into the educational process of pedagogical universities can significantly enhance future teachers' readiness for innovative practice. Students demonstrated growth in both the cognitive component (subject-methodological knowledge) and the motivational component, specifically the desire and confidence to implement new teaching approaches. This observation aligns with the conclusions of T. Molnar (2023), who found that incorporating STEM education into teacher preparation promotes a deeper understanding of complex material, strengthens responsibility, teamwork skills, and the ability to make informed professional decisions.

Our students experienced the benefits of integrated learning firsthand through project work, experiments, and interdisciplinary assignments, which had a positive impact on their attitudes. Notably, the greatest improvement was observed among bachelor's students who initially felt less prepared. This suggests that STEM modules are particularly effective at the foundational stage of teacher education, when students are still open to new methods and can be easily engaged in technology-driven, project-based learning, thus fostering a lasting interest in STEM.

The improvement among master's students was smaller, yet they started with a stronger base. Importantly, both groups ultimately achieved a relatively high level of STEM readiness (67–72% according to the index). This indicates that the implemented measures, including specialized workshops, project-based learning, practical training, and master classes, proved universally beneficial across different levels of teacher education.

The presence of a moderate correlation between the results of the two stages ($r \approx 0.46$) indicates that students who initially showed strong performance generally remained among the top achievers later on. At the same time, the relatively low strength of this correlation suggests that success at the final stage was not entirely determined by the starting level. In other words, the pedagogical intervention significantly reshaped the overall distribution of competencies among the participants. Some students who initially demonstrated gaps were able to compensate for them and reach a solid level of knowledge and confidence. This finding emphasizes the importance of providing targeted support for students with lower baseline readiness. The STEM-based approach can effectively enhance their performance if appropriate conditions are created, such as mentoring, supplementary consultations, and access to learning resources.

Conclusions

The conducted study confirmed the promising potential of integrating STEM education into the system of professional teacher preparation for primary schools. Theoretical analysis demonstrated that the STEM approach aligns with current educational development trends and the goals of the New

Ukrainian School reform. Integrated learning at the intersection of science and technology fosters the formation of competent, creative, and critically thinking teachers capable of educating a generation of students growing up in a highly technological environment. STEM competence should be considered an essential component of a modern teacher's professional competence, encompassing knowledge, practical skills, and innovative thinking.

International experience highlights the need for Ukraine to establish a regulatory and legal framework that prioritizes STEM as a strategic component of national educational policy and serves as the foundation for designing effective teacher education programs for primary schools. For Ukraine, the adaptation of Canadian practices appears particularly relevant, especially those related to post-graduate mentorship systems, partnerships between general and higher education institutions, and flexible formats of professional learning to ensure the sustainable development of STEM education.

The experimental part of our study demonstrated that even relatively short-term implementation of STEM elements (over one semester) can yield a measurable positive effect. Future teachers who participated in STEM projects, practical sessions, and workshops demonstrated significant improvements in both their knowledge and confidence in applying innovative teaching methods. They acquired specific practical skills and, more importantly, strengthened their motivation to experiment in their future professional practice. The average STEM readiness index increased from 59% to 69% ($p < 0.001$), with a correlation coefficient of $r = 0.46$ between the two stages.

It has been proven that the inclusion of STEM components in teacher education programs is both justified and effective, as it prepares future educators to assume the role of facilitators of inquiry-based learning and mentors capable of sparking children's interest in science and technology from the earliest years of schooling.

The prospects for further research lie in expanding the scale of experimental work. It would be worthwhile to conduct a comparative analysis of the outcomes of international STEM education projects implemented across various teacher training institutions. Another promising direction involves tracking how graduates who received STEM-oriented preparation apply innovative methods in real school practice and how these methods influence their students' learning achievements. Further investigation is also needed into specific aspects of STEM competence development, such as the formation of practical skills in using particular technologies (robotics, 3D modeling, and similar tools) in primary school teaching, as well as the psychological readiness of teachers to work in uncertain and exploratory learning environments.

Thus, STEM education opens broad opportunities for preparing teachers who can educate the modern generation using the methods of the future. Its integration into teacher education curricula represents an innovation that ensures continuity between the goals of school reform and the content of teacher training. The findings of our study demonstrate that STEM-oriented preparation contributes to the professional growth of future educators and fosters in them the confidence of innovators and researchers. This, in turn, will guarantee that schools are staffed with teachers who inspire children to explore, create, and think critically while effectively implementing the principles of STEM education in practice.

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

Artem Yurchenko

***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.

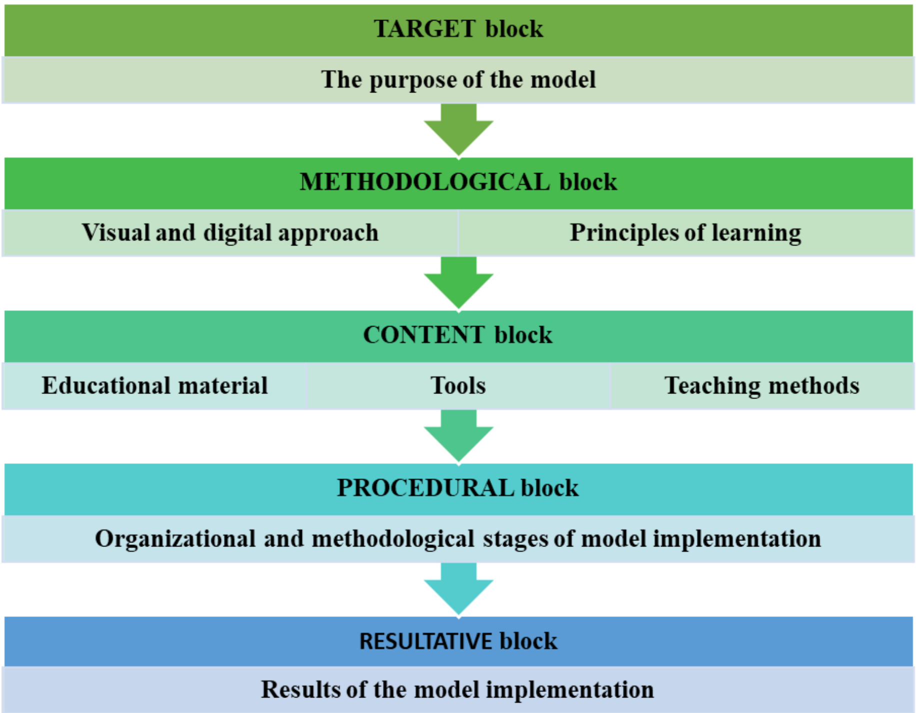

Figure 1. Structural blocks of the model

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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3.3. STEAM-Oriented Vlogging as a Tool for Preparing Pre-Service Foreign Language Teachers

Alla Melnyk

***Abstract**. This study evaluates STEAM-oriented learning vlogs (SOLVs) as a pedagogical tool for advanced university foreign language (FL) teaching, with a focus on developing professionally oriented communicative competence (POCC) in pre-service English teachers. Drawing on human-centred, competence-based, project-based, and inquiry-driven principles, we reviewed Scopus/Web of Science scholarship alongside classroom practice, then conducted a semester-length, two-arm, parallel-group cluster-randomized pilot (N = 60; four intact classes; 5–6 weeks). Classes were assigned to SOLV or a standard research/presentation project (business-as-usual). Outcomes (pre/post) included a POCC proxy rubric (0–20), scored on a teaching-like task; a 5-minute speaking performance measure; a CEFR-aligned mediation task; and a 10-item digital-literacy self-efficacy scale. STEAM content/design quality was tracked in the experimental arm. Results indicate that SOLV strengthens linguistic competence (clearer pronunciation, more precise lexico-grammar) and speech competence in both oral production (greater fluency and discourse control) and mediation (clearer paraphrase, explicitation, and terminology management). Quantitatively, the SOLV group outperformed controls on all indicators: POCC (M_post = 17.3 vs. 14.6), speaking (ΔM = +2.1 vs. +0.8), mediation (13.2 → 15.8 vs. minimal change), and digital-literacy self-efficacy (4.2/5 vs. 3.5/5). Higher STEAM design quality co-occurred with larger mediation gains. Complementary qualitative evidence suggests that hands-on work with mobile apps and online platforms heightens motivation, scientific curiosity, creativity, analytical thinking, collaborative problem-solving, and reflective learning. Taken together, findings position SOLV as a viable, high-impact approach that integrates language development with digital production and inquiry.*

***Keywords**: STEAM-oriented learning vlog, pre-service foreign language teachers, professionally oriented communicative competence, project-based learning, digital literacy.*

DOI: 10.31110/STEM-CaUk-3.3

Introduction

Disruptive technologies are reshaping higher education and imposing new demands on professionals who must work in an environment of uncertainty, creativity, and multiculturalism. AI now permeates education, enhancing learning analytics and employability (Zawacki-Richter et al., 2019), while diversifying the roles of teachers. Accordingly, philological curricula for future FL teachers require re-envisioning. Education-related professions remain essential; automation cannot replace them (Melnyk, 2023).

Amid rapid change, educators must continuously refine their skills, adapt quickly, and practise self-direction. Methodology scholars emphasise the need to develop professionally oriented communicative competence (POCC) (Borysko, 2018), with increased attention to intercultural training in speciality 014.02 (Secondary Education). In line with these demands, intercultural (general-cultural, academic, and professional) FL education should both build POCC and foster learner autonomy. Introducing STEM/STEAM elements and strengthening cross-disciplinary links between practical language classes and psycho-pedagogical courses can advance these aims.

A STEM/STEAM-based model cultivates POCC through practice, self-directed learning, independent inquiry, and creative experience. Centred on project-based learning**,** it begins with single-discipline projects and scales to integrative designs spanning science, technology, engineering, mathematics, and the arts. STEAM thus serves as an integrated, project-driven approach that marries methodological and pedagogical aims. It promotes creativity, critical thinking, and problem-solving, while inquiry-based study provides the intentionality needed to teach and assess 21st-century skills. Within this frame, a SOLV offers a uniquely integrative experience that develops speech, linguistic, learning-strategic, and sociocultural competencies in pre-service English teachers.

Research Results

Within a competence-based framework, the practical aim of FL teaching is to form the ability to organise effective FL communication (spoken and written) across professional domains (Methodology, 2011, pp. 262, 66). POCC comprises four components: speech, linguo-sociocultural, linguistic, and learning-strategic, each with profession-specific elements. In light of the CEFR Companion Volume's emphasis on mediation and interculturality, mediation competence becomes pivotal for inclusive, effective classroom interaction (Melnyk, 2025).

Deepening international interaction among specialists in various fields calls for an expanded set of FL communicative subcompetences essential for effective intercultural communication. The role of the mediating professional, capable of conveying information and building "bridges between cultures" in writing and speech, is therefore increasing. The professional functions expected of teachers require mastery of a range of skills critical to success in their field, particularly those tied to professional mediation activities. Graduates must be able to devise sound personal strategies, apply specialised knowledge in real intercultural exchanges while accounting for linguo-sociocultural factors, swiftly gather and systematise new data, and adapt to rapidly changing information flows, among other tasks.

We maintain that a pre-service teacher's POCC represents an advanced, field-specific level of communicative mastery. In professional contexts, teacher candidates guided by their pedagogical perspectives and motivations must skillfully adapt acquired knowledge, interpret and apply linguistic and sociocultural resources, and deploy learning-strategic language skills in reading, writing, listening, speaking, and mediation to foster effective FL interaction and pedagogical communication. Students are therefore expected to employ a range of communicative strategies and complete professional tasks in academic and workplace settings. Because future FL teachers' POCC encompasses the attitudes, knowledge, and skills necessary to communicate effectively both orally and in writing, and to utilize the target language as a practical tool in intercultural settings, this competence must be purposefully cultivated.

POCC is nurtured chiefly through philological disciplines that address the psychological, methodological, pedagogical, and cultural facets of the teacher's professional identity. Achieving this goal requires systematic cross-curricular links between practical language classes and psycho-pedagogical courses. Integrating STEAM content further enriches the process by providing authentic, problem-based contexts that strengthen language use and pedagogical expertise.

International experts on STEAM implementation note that "a STEAM-oriented teaching methodology is based on project-based learning, problem-centred study of science and mathematics subjects, and learners' independent creation of new educational values for themselves. It emphasises collaborative and networked practices in learning, research, and artistic projects that illustrate how scientific knowledge can be embodied in the creation of art objects." (Marchenko, 2020).

The term "STEAM education" has been conceptualized variously: as a movement seeking innovative pedagogical experiences; as integrative classroom practices aimed at solving real-world problems; as an integrated instructional approach; and even as a comprehensive educational model. Regardless of terminology, scholars agree that teaching and learning should focus on practical projects that enable students to understand, evaluate, and address the technical and scientific challenges encountered in both everyday and professional contexts.

In recent years, the STEAM literature has documented the positive impact of innovative practices and instructional experiments on students. The theoretical foundations of STEAM educational practices and technologies are discussed in the works of Ukrainian educators and psychologists S. Dotsenko, S. Podlesnyi, and O. Tarasov (scientific discourse; educational practices and technologies of STEAM education); N. Polikhun and I. Slipukhina (STEAM in formal and non-formal education); O. Patrykeyeva, O. Korshunova, N. Hushchyna, and I. Vasylashko (professional development of teachers in STEM contexts).

Internationally, STEAM implementations vary. Research-led teacher education in Finland connects science with everyday artefacts (Haatainen & Aksela, 2021; Haatainen et al., 2024; Aksela & Haatainen, 2025). Spain has documented inquiry-based, integrated STEAM modules in higher education (Aguilera & Ortiz-Revilla, 2021; Ortiz-Revilla, Adúriz-Bravo, & Greca, 2020; Ortiz-Revilla, Greca, & Arriassecq, 2022; Ortiz-Revilla, Ruiz-Martín, &

Greca, 2023). In Canada, efforts span community STEAM camps linking coding and mathematics (Bertrand & Namukasa, 2020; Bertrand, Namukasa, & Li, 2023), Two-Eyed Seeing approaches in Indigenous STEM (Hogue, 2016; Martin, & Hogue, 2019), maker-centred teacher PD (Hughes, Morrison, & Robb, 2021), modelling in K–12 STEM teacher education (Ben-David Kolikant, Martinovic, & Milner-Bolotin, 2020; Martinovic & Milner-Bolotin, 2021), and playful integrations of mathematics, coding, and music (Gadanidis et al., 2017). The literature converges on practice-orientation and integrated, project-based pedagogy (Belbase et al., 2022; Bautista, 2021).

Technology within STEAM reduces cognitive load and enhances motivation (Costley & Lange, 2017). Evidence supports gains in student learning (Gao et al., 2020) and professional development (Shernoff et al., 2017). At the same time, recent work notes that many pre-service teachers feel underprepared to foster digital competence; non-STEM students and those with teaching practice reported lower perceived readiness than STEM peers and those without practice (Dolezal, Motschnig, & Ambros, 2025). Programmes, therefore, need coherent, institution-level strategies to integrate digital skills throughout the curriculum.

In discussing the phenomenon under study, Asoiants and Ivanova (2014) note that the ICT tools introduced into educational processes – although not designed exclusively for solving educational tasks – possess "enormous didactic potential for creating an information-rich learning environment" (p. 92). Prayudi et al. (2021) add that technology in language learning should not be confined to search engines used merely to look up extra details on a topic; rather, it can be harnessed to make learning more efficient, adaptive, and engaging. The use of relevant activities and a broader range of technological resources has led to new pedagogical innovations in language study (Chapelle, 2019).

The use of authentic video materials in English-language teaching (ELT) has been the focus of numerous studies. Researchers have developed strategies for using English-language television news in university ELT courses (Vikovych, 2010), online audio and video materials for teaching professionally oriented listening and formation of students' English communicative competence in technical universities (Volkova, 2015), It has been demonstrated that using authentic video blogs is advantageous for developing pre-service teachers' competence in professionally oriented English speaking (Duka, 2019). It has been proposed that methods for jointly developing pre-service teachers' professionally oriented speaking competence and ICT competence through webquests and modern internet technologies (YouTube, Google Hangouts, Google Classroom, Skype) (Burak, 2019). ICT tools, together with free mobile apps, online services, and platforms, prove valuable for creating interesting and original projects envisioned in the curriculum.

In language education, Web 2.0 tools, including blogs, vlogs, wikis, and podcasts, facilitate authentic multimodal tasks. Research shows that vlog projects can aid vocabulary growth and broaden lexical range (Ajabshir & Sadeghi, 2019), improve speaking and engagement (Huang, 2021; Kristiani & Pradnyadewi, 2021; Misdi et al., 2021), and strengthen both oral and written production (Cahyana, 2020; Pratama, Arifin, & Widianingsih, 2020). Vlogging supports autonomy, public speaking, metacognition, and motivation (Lestari, 2019; Rakhmanina & Kusumaningrum, 2017), making it a strong candidate for POCC-aligned tasks. Integrating FL vlogging into coursework enables students to select topics aligned with their interests and specializations (Demetriou, Papageorgiou, & Efstathiades, 2022).

The vlog phenomenon cannot be separated from the blog, because a vlog, short for video blog, is essentially the fusion of video and blogging. A blog is, in itself, a forum for anyone wishing to voice an opinion or share information, whether privately or publicly. Researchers Naboka & Demchenko point out that the most successful educational blogs share certain features: regular posting, collaborative authorship, the inclusion of multiple media types, original (author-generated) content, as well as autonomy and mobility (2019). Although blogs were initially created for educational purposes, they soon attracted FL instructors because they enable the creation of electronic, multimedia journals without requiring specialized programming knowledge (Wu, 2006, p. 69).

Andrusiak argues that a blog, by its very structure, combines features of both spoken and written communication and therefore calls it a "third mode of interaction." The author distinguishes five main blog types: text blog contains primarily written information; audioblog hosts a variety of audio material; photoblog consists mainly of photographs; videoblog (vlog) presents content in video form; podcast is a digital media file distributed online for playback on media players or personal computers (Andrusiak, 2015, pp. 18-20). Thus, while the videoblog (vlog) is recognised as a distinct category of blog, the difference lies in its specific mode of content delivery: blogs are typically used for text production, whereas vlogs foreground audiovisual interaction.

Researchers concur that this technological tool, when used in language classes, fosters students' autonomous learning and reflection on their learning process (Lestari, 2019). The key idea is to give students opportunities to practise the target language while creating vlogs. Publishing their videos on sharing platforms such as YouTube makes the learning experience more engaging, as learners can observe, study, and practice after watching how something is done in the video (Harefa, 2020).

English-language scholarship describes a vlog as a visual medium that delivers a continuous stream of online broadcasts, enabling anyone to upload and share videos that function simultaneously as audiovisual life-logging and as a communication channel (Maulidah, 2018). We concur with the author's conclusion that creating vlogs fosters autonomous learning, as students gain a clearer sense of purpose and the freedom to manage their own ideas throughout the learning process. Moreover, videoblogging encourages public speaking, supports communication and self-discipline, enhances social interaction, nurtures metacognitive awareness, and strengthens intrinsic. These findings suggest that vlogging technology is particularly well-suited to highly motivated learners.

From a pedagogical standpoint, videoblogs can serve as both primary and supplementary resources in language instruction. Teachers, for example, can use authentic video content created by and for native speakers in practical foreign-language classes. To develop specific language competencies, students might be directed to explore blogs and vlogs such as BBC Learning English for vocabulary work on idioms, phrasal verbs, and accurate word choice; Grammar Revolution for grammar explanations, usage practice, and tests; and Espresso English for pronunciation and intonation practice using audio and video materials. Interaction with native speakers via blogs and vlogs, e.g., MyEnglishTeacher.eu, also promotes spoken English competence by providing opportunities for brainstorming, self-presentation, information exchange, increased speech rate, improved pronunciation, and greater precision in expressing ideas.

Building on scholars' observation that video texts can effectively simulate an authentic language environment in the classroom, we may assume that vlogs are particularly useful: they mirror contemporary speech, abound in idiomatic expressions and stylistic features, and thus replicate an English-speaking milieu where one might otherwise be absent.

In addition, a vlog offers an immersive experience by combining video, audio, images, and text, thereby enriching both informational content and the emotions conveyed to viewers (Safitri & Khoiriyah, 2017). Vlogs offer multisensory integration, encompassing visual, auditory, kinesthetic, mixed, linguistic, situational, pattern-based, object-oriented, and imaginative elements, showcasing not only the auditory facets of language but also non-verbal communicative signals, such as paralinguistic and extralinguistic cues. The clear advantages of vlogs as instructional video materials include their rapid and user-friendly access, as well as the flexibility they afford in classroom use.

A video blog presupposes a real or at least semi-real audience, such as peers, pupils, or even parents. This authentic communicative goal raises the stakes for clarity, accuracy, engagement, and accessibility, compelling students to make instructional decisions that mirror genuine teaching steps: *What does my viewer already know? Which visuals best explain this concept? How slowly should I speak?* Learner autonomy grows because students control the topic, sequence, design, and delivery of the material.

Vlogging also helps future teachers capture their thoughts and questions while showcasing their work to a broad audience. They can comment on current events, respond to course topics, or expand on ideas discussed in class. Maintaining a vlog trains advanced learners to write for an audience and to practise their own "voice." Vlogs blend conversational, academic, and professional English with on-screen text, visual effects, props, diagrams, and captions, providing an experience that prepares pre-service teachers to deliver multimodal instruction in technology-rich classrooms.

When used as authentic tasks**,** vlogs heighten engagement and deepen learning. They are flexible: students can work individually or in small groups, and the finished product can serve as both a unit-ending assessment and evidence of learning across an entire module. Such activities create student-driven platforms that involve everyone; most importantly, they foster effective collaboration and critical thinking. Because the tasks mirror real-world communication, learners individualize their projects, sharpen critical thinking skills, and practice autonomy, innovation, and adaptability.

Given the need to prepare FL teachers who can both engage in and teach intercultural communication (Borysko, 2018), our program requires candidates to develop their own learning vlog projects, both in class and independently. Each project combines pedagogical and STEAM components, benefiting both the trainees and their future learners. The aim is to strengthen learning-strategic competence as a foundation for students' professionally oriented linguistic, speech, and linguo-sociocultural competences.

Following Ustymenko, we define an instructional project as a set of tasks and exercises designed to organize learners' creative, inquiry-oriented, and independent FL communication with the aim of solving a relevant, practically significant problem, whose outcome is a concrete product (Ustymenko, 2017). A FL project is characterised by purposefully structured, extended, and meaningful creative activity; the existence of a tangible end product; and learner autonomy in planning, execution, and presentation.

We consider that a professionally focused vlog project can develop intercultural FL communication skills among educational professionals, provided specific guidelines are followed. These include a) establishing clear project goals that mirror real-world professional practices, b) designing tasks that simulate authentic professional challenges to spark interest in language and cultural teaching, and c) structuring work inside and outside the classroom to enhance sub-competencies (Melnyk, 2024). Such a project work engages five language modes: listening, speaking, reading, writing, and mediation, while integrating knowledge, skills, and abilities from other disciplines. The approach encourages reflective practices to overcome encountered challenges, emphasizing self-assessment and improvement.

Drawing on established project typologies (Arvanitopulo, 2007), the SOLV aligns most closely with the information-research type: students curate, present, and analyse STEAM-related content alongside psycho-pedagogical and cultural material, often incorporating elements of scientific inquiry for a real audience. *Science* addresses causal explanations, hypotheses, experimental procedures, and evidence; *technology* presents functional descriptions and user instructions; *engineering* frames problem statements, constraints, and design solutions; *art* conveys narrative structures, visual composition, graphic annotation, and audience engagement; and *mathematics* relies on comparison and the interpretation of charts and data trends.

STEAM topics place learners in cognitively demanding language spaces (explaining mechanisms, describing procedures, marshalling evidence, specifying functions and instructions, defining problems and constraints, composing visuals for audiences, and interpreting data), making SOLV a natural vehicle for integrated language-and-content development.

A SOLV is therefore instructional in form yet professional in content**,** sketching the contours of learners’ future work while integrating the disciplines signalled by STEAM. Hallmark features include collaboration**,** authentic audiences and assessment**,** interdisciplinary links**,** multiple solution paths**,** and quasi-professional tasks that cultivate attitudes, motivations, and interests. The value lies not only in the language artefact but in repeated engagement of all language modes.

Reading. Scientific/technical texts are multimodal (tables, graphs, measurements). Training pre-service teachers to read across modes builds source comparison, main-idea recognition, and selection of audience-appropriate infographics. Annotation sharpens attention to discourse markers and patterns (e.g., passive voice in reports) and strengthens critical reading.

Writing. Drafting scripts, on-screen titles, diagrams, captions, and reflections develops genre control. Learners transition from conversational voice-over to procedural prose, incorporating accurate scientific facts into creative texts; digital tools facilitate iterative, linked, individual, or collaborative production.

Speaking. On-camera explanations require clear pronunciation, signalling (“Let’s review…”, “Three factors…”), and real-time descriptive language, especially for demonstrations.

Listening. Students analyze model explainers, critique peers’ footage, monitor their own recordings for clarity, and respond to viewer questions, listening both for precision (terminology and sequence) and global meaning.

Mediation. Learners recast complex ideas into accessible language; summarise data for lower-proficiency peers; coordinate team communication; and produce multimodal supports (bilingual glossaries, visual organisers, interactive quizzes) that bridge knowledge gaps and promote inclusion. These mediation moves, paraphrasing, precise lexical choice, and audience-aware explicitation are central to the CEFR. Distilling dense multimodal input strengthens reasoning and summary skills essential for lesson planning; deciding when to retain L1 technical terms versus explaining them in L2 builds the metalinguistic awareness required for English-medium teaching. By creating explanatory vlogs with layered supports (visual cues, captions, data commentary), future English teachers rehearse the mediator’s role and practise inclusive pedagogy.

Students typically respond to the brief with a mix of nervousness and enthusiasm, energised by the chance to produce an instructional artefact of their own. The SOLV brings together STEAM content, digital production, and reflective practice to develop POCC. A typical cycle spans five to six weeks. *Design phase (Weeks 1–2).* Students independently research the topic, consult multiple sources, evaluate credibility, extract key ideas, and practise both concise and extended explanatory summaries. In class, they brainstorm, analyse exemplar vlogs, exchange ideas, and agree on a shared plan. *Script & storyboard (Week 3).* Learners draft a concise script, plan visual elements (titles, on-screen text, and multimodal cohesion), verify facts, and edit for clarity and accuracy. Explaining content in English develops questioning, reasoning, and multimodal description skills, the academic registers students will need in future teaching. *Production (Weeks 3–4).* Students film, rehearse clear delivery, address pronunciation issues, and edit footage in low-threshold mobile apps (e.g., InShot, FilmoraGo, Movavi Clips, VivaVideo). Typical edits include trimming, transitions, captions, audio balancing, and basic effects. Finished projects may be recorded via Flip (Flipgrid) or uploaded to Padlet, Google Sites, or Microsoft Teams. Filming follows the script; final editing completes the video. *Feedback & refinement (Weeks 5–6).* The vlog is evaluated from multiple angles, with targeted feedback highlighting specific issues. Students re-record as needed to improve fluency, intelligibility, and discourse organisation. Final videos are posted on the university platform and channels promoting FL study. *Reflection.* Learners keep brief journals and give peer/teacher feedback. Reflection via self-assessment, peer review, and one-on-one conferences consolidates skills and sets new goals. Self-monitoring through playback fosters metalinguistic awareness (e.g., "I dropped past-tense endings, re-record").

A recent unit on learning strategies culminated in the creation of virtual posters, short videos, and interactive infographics (using Canva, Google Slides, and Screencastify). During the showcase, peers left questions and feedback on digital "sticky notes." As one student observed, "I never thought my project would teach anyone, but my younger brother watched it and started asking questions." That sense of ownership and confidence is precisely what a well-executed project can foster. By speaking to the camera, students practise public speaking, sharpen their idea presentation, and build self-assurance

In an English-medium setting, we cannot assume that every learner will display the expected degree of autonomy; otherwise, the educational payoff of producing a vlog may be unacceptably low. To address this, we have created a structured Project Log that shows how STEAM-oriented vlog projects build learner autonomy, digital literacy, and pre-service English teachers' POCC. The log serves as a step-by-step guide to the vlog workflow, including scheduled consultations and free tools such as Google Calendar, Google Meet, and Google Classroom, to streamline planning and resource sharing.

We illustrate this approach with a specific Project Log from an English-language course, themed "Boost Your Memory." The SOLV brief places students in a quasi-professional scenario: You are an *FL teacher who recognises that vlogs on memory techniques can greatly improve learners' recall of vocabulary, grammar rules, and idiomatic expressions, thereby boosting their proficiency and confidence. Create a learning vlog that offers accessible, engaging, and practical strategies for different learning styles, making English study more effective.* This scaffolded sequence guides students from initial problem framing through research, scripting, filming, and reflection, ensuring that each stage contributes meaningfully to the development of both professional skills and communicative competence.

PROJECT LOG

Step 1: Inquiry and investigation of the best memory techniques for learning.

<u>**Project Block 1:** Prioritize typical problems in learning foreign languages and share your personal experience.</u>

1. Individually, rank your list of problems or mistakes that speakers frequently encounter. This could be a confusing grammar rule or a tricky pronunciation issue. Demonstrate an understanding of why this problem is particularly challenging, perhaps by sharing examples from life and real-world studies.

2. Compare your list with other members of your group. Explain the reasons for your choice with examples from your own observation.

3. Work with someone from a different group. Compare your group's answers to the questions with those of the other group. How were your answers different?

4. What set of problems did you share in the discussion in task 2 that you would later include in your vlog?

5. Read one of the articles exploring learning techniques (https://www.fluentin3months.com/memory-palace/; https://www.pinterest.co.uk/pin/543951079912554 89/; https://www.pinterest.co.uk/pin/the-feynman-technique-for-learning-556124253997388137/).

Discuss the questions.

- What type of learning strategy do you think learners use most? Why?
- What do you use regularly? Which do you never use?

6. Imagine you are talking to your young brother. With your partner, explain which learning strategy would be better to apply? Give three reasons.

7. Fill in the table given below by sharing a set of techniques for memorising information in learning English / Ukrainian / French/ German.

	Kinds of memory techniques	*Identify the «plateaus» and difficulties*	*How to demonstrate a memory strategy*
1	A 2-line poem / a rhyme		
2	An acronym		
3	Memory palace (Cicero's method)		
4	An icon (visualization)		
5	An association of ideas		
6	The spaced repetition of language usage in various contexts		
7	Correlation with the learner's native language nuances		

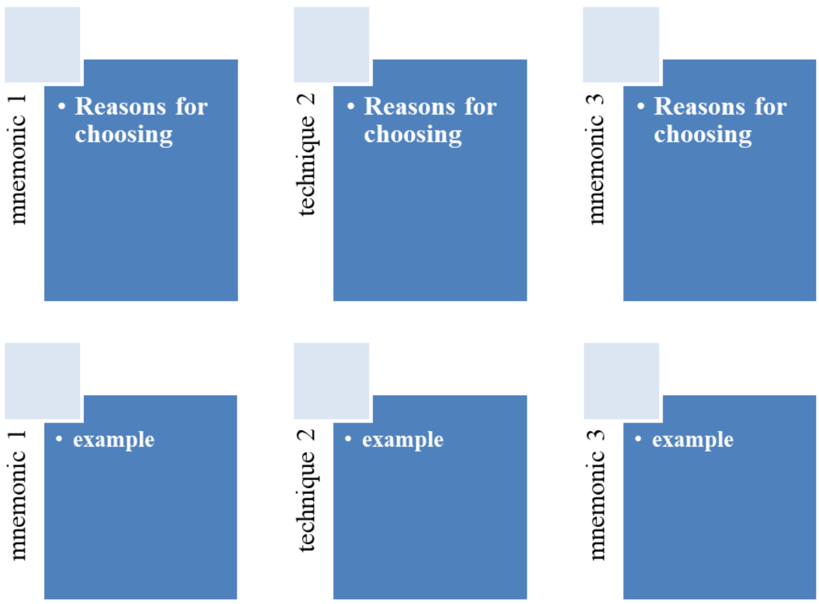
8. Choose three techniques in order of how significant they have been for studying. learning foreign languages? Explain the reasons for choosing them.

Project Block 2: Think of ways in which you can demonstrate memory techniques. Fill in the diary with a short summary of each kind.

Learning strategy 1 - Educational vlogging focus - Project diary

The term «project dairy» can be used in the context where tracking the progress of a project is crucial. In the Project diary, the changes in timelines, advancements, and setbacks of the design project are meticulously recorded. In this instance, the Project diary serves as an official record-keeping tool to track all developments within an ongoing project, providing useful information for future reference.

Project diary – My mnemonics/techniques



Step 2: Collect information about the strategies to enhance memory and share evidence

Project Block 3 Research storyline iterations

1. Read *the learning strategy*. Then work in pairs. How useful do you think this framework would be for creating your vlog? Have you followed / would you like to follow this scheme? Why? / Why not?

Learning strategy 2 - Educational vlogging focus - Incorporating a 5-stage framework

To improve content quality and engage viewers, apply a 5-stage narrative framework. It can help in creating a compelling narrative that keeps viewers engaged from start to finish. However, it is essential to remember that vlogging, by nature, can be more spontaneous and free-form than other types of storytelling. While these stages provide a useful guideline, vloggers should feel free to adapt, merge, or skip stages as they see fit based on their content and personal style.

When creating a learning vlog, it's essential to remember that learners will appreciate both the introduction of new, sophisticated techniques and the refinement of strategies they may already be familiar with, thereby reinforcing their existing knowledge base. Making the vlog interactive with prompts for viewers to familiarize themselves with. The vlog should strike a balance between introducing new concepts and practicing and reflecting on the techniques in real-time, which can enhance the educational value of the content.

Throughout the framework, it is important to maintain a friendly and supportive tone. The content of vlogs should be concise, relatable, and engaging, as this encourages viewers to engage more deeply and not to be afraid of making mistakes. Good editing, clear visual aids, and high-quality audio are also key in creating an effective learning vlog. For instance, diagrams for story techniques or charts for spaced repetition systems (SRS) can be particularly helpful at this level, as they cater to visual learners and break down complex information into digestible pieces.

2. Read sentences 1-5 and discuss which techniques of a 5-stage narrative framework they relate to.

1. Relatable challenge and brief personal anecdote: "I kept forgetting irregular verbs before exams." Reframe the struggle as a productive challenge that can boost learning if we use the right strategy.

2. Use the technique Demo and visually show the mnemonic. Build step-by-step; animate text, icons, sketches. Say *why* it works (link to memory research / cognitive principles). Include at least one worked example from English learning (vocabulary, grammar, collocations, pronunciation).

3. Reflect / evidence/transfer. Rapid recap of key steps & benefits. Cite a supporting source ("According to X, spaced repetition boosts long-term retention…"). Invite viewers to try the technique this week & report results (feedback loop). Close the mystery: reveal the answer to the opening puzzle or re-test the original quiz to show improvement.

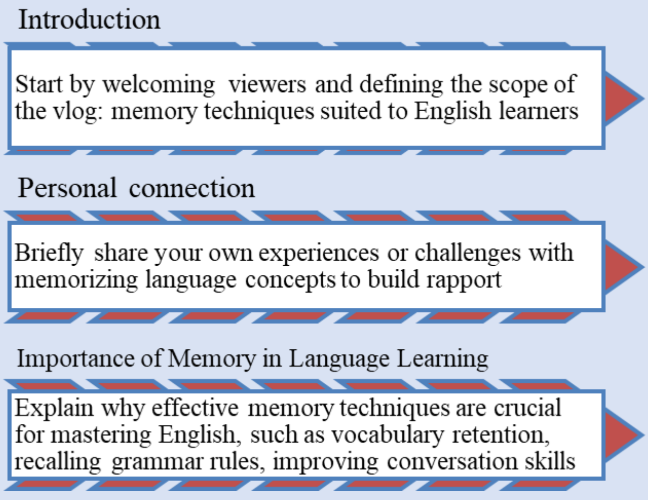
4. Spark curiosity; show a puzzling memory fail or a quick quiz. Raise a question viewers want answered ("Why can I remember Netflix plots but not phrasal verbs?").

5. Guided practice / Viewer participation – Prompt viewers: "Pause and build your own image/story for these 5 verbs." Use on-screen cues, countdowns, or "Comment your version below" to create an interactive segment.

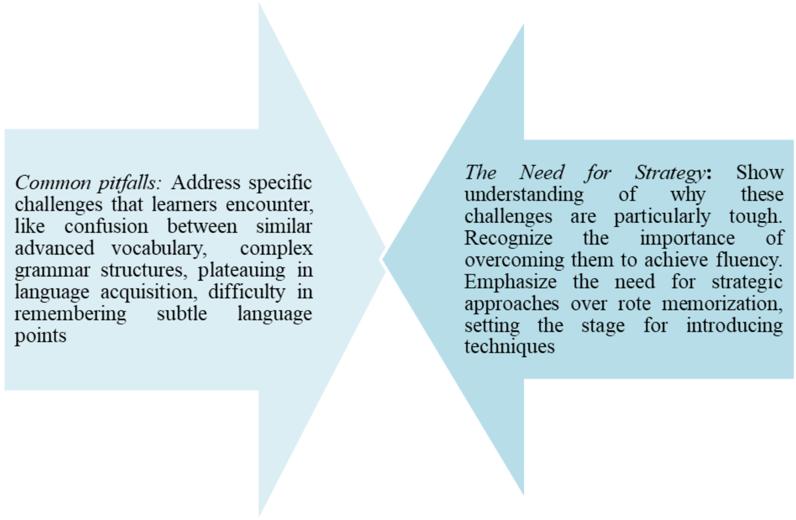
FRAMEWORK

Stage 1. Orientation – Introduce the viewer to the context. This could include your location, the purpose of the vlog, the main characters involved, or any other element that sets the scene. By establishing a clear context, you help the viewer understand and become invested in what they are about to watch.

Setting the Context



Stage 2. Crisis – Present a problem, challenge, or question. For vloggers, this might be a personal challenge they're taking on, a question they seek to answer, or an unexpected situation they find themselves in. This is what hooks the viewer and compels them to keep watching to find out what happens.



Stage 3. Journey – Detail the process or adventure undertaken to resolve the crisis. It's the bulk of the content. In vlogs, this could involve traveling, exploring, trying out new things, or simply navigating through educational content. The journey should be engaging and demonstrate progress or change.

Exploring and Applying Memory Techniques

Guided learning path: Present a range of memory strategies to address the challenges you identified.

In-depth demonstration: Dive into each technique. For example, show how to build an imaginative story to remember a series of phrasal verbs, or demonstrate how to use spaced-repetition systems (SRS) effectively.

Interactive segment: Engage viewers by prompting them to create their own mnemonics or stories from a sample list of tricky words or language rules provided in the vlog, turning it into a dynamic learning experience.

Stage 4. Discovery – Share new insights, learning experiences, or solutions to the problem the learner can face up to. This can be a moment of reflection, realization, or a tangible outcome. For vloggers, it's essential to share these insights with their viewers, as they add depth to the story and often provide value or a takeaway for the audience.

Gaining New Skills

Reflect on effectiveness. After demonstrating the techniques, share examples of how these methods help retain new information and enhance language acquisition, and what didn't.

Evidence. Provide testimonials or evidence from available (linguistic) research to show that these techniques have proved effective for other learners.

Self-reflection Urge viewers to experiment with each technique to find which works best for them, fostering a sense of autonomy in their learning journey.

Stage 5. Resolution – Conclude the vlog by resolving the situation, overcoming the challenge, or ending the story. This provides closure, leaving viewers with a sense of satisfaction.

Consolidation and Closure

Review the Essentials. Briefly restate what the vlog covered and the memory strategies demonstrated, highlighting the most useful ideas and explaining why they are helpful. Think about why the featured memory strategies help retention (link to at least one cited source).

Put It Into Practice: Encourage students to start using these memory tools in their everyday study sessions. Invite learners to apply one technique in their next study session or vocabulary list. For instance, post your 5-word story below.

Join the conversation. Invite viewers to post their results, questions, or additional memory tricks that work for them so everyone benefits from a shared learning community. Which mnemonic worked? What variation did you invent? Which text type gave you the clearest explanation? Build a peer community.

Project Block 4: Research sources that illustrate the memory techniques

1. Read *the learning strategy*. Find support to defend your ideas as viewers trust evidence. Move from a simple opinion to a defended claim by adding a *source* + *relevance*. Go to your class textbook for pictures, diagrams, and quotations. Use the Internet to search for your topic, using only reliable sources and up-to-date information. Check out documentaries, news videos, and texts such as journals and newspapers. If appropriate, include anecdotal evidence, verifying as much information as possible.

Learning strategy 3 – Educational vlogging focus – Defend ideas

When preparing your evidence and support for an academic context, make sure to take good notes and include the speaker/author, title, and date of the presentation or article (using a notecard for each source of information can be helpful). Also, when you use quotations or paraphrases, be sure to give credit to the original source.

Example of How to Defend Ideas in Speech

Notice how, in this simple opinion, the speaker makes their view clear but fails to provide any support for it. By pointing out her agreement with Veronica from *Change Is in the Making*, the second speaker defended her position.

Simple opinion	*Defended opinion*
1. *My view is* that too many people are afraid of change because they think it's going to be uncomfortable and hard.	2. While many people are reluctant to change, *I agree with Veronica Collins* that, in addition to making people emotionally uncomfortable, change can also lead to human flourishing.

Effective speakers also defend their use of an idea or example by showing how it supports their argument and why their source is relevant and valid.

Simple opinion	*Defended opinion*
3. *I believe* it will be difficult for the Mongolian herders to preserve their culture and traditions because no one respects their culture these days.	4. *Morgan Kay* is a biologist from Colorado who works for an NGO in Mongolia. When discussing the nomads' chance of survival, it is essential *to remember her point* that the Western way of life is not the only way.

Synthesize the content, ideas, and vocabulary from these lessons, noting the attributes of the concepts of resilience and perseverance, as well as the benefits of a growth mindset in education and personal development. Craft engaging elements that use the vocabulary to inspire and motivate your audience to adopt a more positive mindset towards learning and growth, and make eustress work for them.

2. Read about different types of text and answer the questions.

1. What type of academic literature is the most difficult to read? Why?

2. Why will learners be required to read academic literature, journal articles as they progress in their academic career?

3. What do journal articles usually report?

4. What organizational structure do websites typically follow?

5. What types of academic essays do you usually write? Why?

Common text types and how they are organized

Text type	*Organization of information*
Textbook	-logical order, simple → complex -divided by chapters and headings -topic sentences give main ideas; concluding sentences summarise paragraphs
Report	- opens with a summary/highlights section listing main points -body split into headed sections -often uses charts, tables, or graphs - may finish with recommendations for action
Academic essay	- formal structure -thesis at the end of the introduction previews the content -body paragraphs follow the order set out in the thesis - conclusion restates the main argument and summarises the content
Newspaper/ magazine article	- short paragraphs - main facts (who, what, where, when, why, how) appear early - details and elaboration follow - may include direct quotations from experts

Journal article	-abstract previews the paper -standard sections: abstract, introduction, methods, results, conclusion
Website	-layout varies with purpose -overview usually given in top or side menus - key information is hyperlinked directly from relevant words for quick access

3. Read *the learning strategy*. Find the underlined sentences in the article. Decide which words were left out using ellipses.

Learning strategy 4 - Understanding text structure

Writers use *ellipses* to avoid repeating words and structures that they have already used. If you don't understand part of a text, it could be because the writer has used ellipses. Reading the preceding phrase, sentence, or sentences should help you understand what the writer means.

Academic literature in a language other than your first can be challenging 1(…), but certain strategies can boost both comprehension and reading speed.

Helpful seven-step routine: "Read it fast, use it smart."

1. <u>Skim the passage first 2 (…) what's it about?</u>

2. <u>Link new ideas to what you already know (or want to learn) 3 (…) prior knowledge makes material stick.</u>

3. <u>Predict the structure 4 (…) journal article, report, essay?</u>

4. <u>Chunk the text: divide it into sections and add your own headings 5 (…) or use the author's.</u>

5. <u>Turn each heading into a question (e.g., "What is the loci method?") 6 (…) self-queries sharpen focus</u>.

6. <u>Read each chunk carefully to answer your questions 7 (…) jot margin notes if the details are dense.</u>

7. Reflect when you finish: What's new? What helps? 8 (…) What still isn't clear?

4. Decide what statements a-h you would choose to explain the underlined sentences 1-8.

a. but you can use certain strategies

b. …to get a sense of its content, length, and text type.

c. …new material sticks better when you link it to prior knowledge or personal interest. *Where have I seen this in class?*

d. …how the ideas will be organized by using what you know about the text type. *Is it a …?*

e. …to find the answer to the question you have generated. If the information is complex,

f. If you were not given a set of questions to answer, develop a set yourself by turning each heading into a question. *How was the study done?*

g. …that reflect the content of each section. If a reading has already been divided into sections, use the writer's headings.

h. … on the content of a reading when you have finished. *What's new? What helps my learning? What's unclear? What did I learn that was new, interesting, or important? What do I not understand or need to ask someone about? What opinion (if any) do I have about the information in the text?*

5. Read the *learning strategy* and analyse the example of an explanatory synthesis essay. What information about writing this type of essay most surprises you?

Learning Strategy 5 - How to Write an Explanatory Synthesis Essay

An explanatory synthesis essay shows how information from one source applies to another source. One source may be theoretical, while the other source may describe an individual's experience. The goal of this type of essay is to apply theory to experience.

- Like all essays, an explanatory synthesis essay must have three general sections: an introduction, a body, and a conclusion. You may not use section titles as headings in the essay.
- The introduction announces the topic of the essay. Although there are many good ways to start an essay, the introduction usually begins with a general statement about why the topic is important.
- The introduction finishes with a thesis statement. A thesis statement is a sentence that includes the topic of the essay and the opinion that the essay will present. The opinion expresses whether the theory (from the first source) applies, or does not apply, to the experience (from the second source). It may or may not include the main reasons why the opinion of the essay is correct.
- The body of the essay contains a number of paragraphs. As in other types of essays, each paragraph usually explains one reason why the essay's opinion is correct.
- Each body paragraph should start with a topic sentence that clearly indicates the topic of the paragraph. You can do this by repeating key words (or synonyms of the key words) from the thesis.
- Within each paragraph, refer to both your sources. Start by referring to your first source, use a transition phrase or sentence, and then refer to your second source.
- Each body paragraph should finish with a sentence that makes the point of the paragraph clear.
- The conclusion summarizes the main reasons why the essay is correct. It often finishes with a sentence that restates (but does not repeat) the thesis.

Example Explanatory Synthesis Essay

Task: Summarize Johnston’s (2003) article on the morality of testing and assessment and apply it to your partner’s English-language testing experiences.

Summary of information to be synthesized

Reference	Johnston, B. (2003). *The morality of testing and assessment*. In *Values in English language teaching*. Mahwah, NJ: Lawrence Erlbaum Associates.
Article	-assessment is a moral activity -testing assigns value or worth with serious consequences for students - damages the teacher–student relationship - measures only the knowledge that the teacher values - test preparation courses may be unethical
Student experience	- Ayşe Mehdi, age 22, from Saudi Arabia -received a government-funded scholarship for a year of English-language training and two years of a Master of Engineering degree - must pass the English-language program with 75 percent and a TOEFL iBT score of 90 - English test scores must be submitted within one year

Writer's plan

Introduction	-describe the student's learning background, goals, motivation, funding, and required standardized tests. -apply the theory from the article to the student's experience.	
Body	*Article*	*Student experience*
-consequences	-standardized tests have serious consequences. -a student's worth is seen as dependent on test scores.	-feels pressure to improve. -worries she will feel she has failed herself and her family. -may lose government funding. -her future plans could be affected.
-teacher-student relationship	-teacher–student relationship is important. -teachers should be supportive in class. -testing can harm the	-enjoys both teachers and classes. -doesn't see test precautions as a lack of trust.

	teacher–student relationship.	-if she fails, her teachers will be upset.
-knowledge to be tested	-tests often measure only what teachers value.	-learned knowledge from outside the classroom isn't reflected in tests. -example: "I feel like a coffee."
-test preparation	-test preparation can be unethical. -often focuses on raising scores without improving actual proficiency.	-doesn't believe test preparation is unethical. -thinks her teachers help her improve her proficiency.
Conclusion	Some moral implications of testing are reflected in the student's experience, while others are not.	

Checklist when citing evidence in the vlog

- Identify *who* (author/expert/organization).

- Give the *type of source* (journal article, textbook diagram, reputable website, classroom study).

- Provide *date* (year is fine in video).

- Say *why it matters here* ("This applies to language study because…").

- Distinguish *data* vs *anecdote*. Anecdotes are okay if labeled and tied to research.

Useful Phrases for Citing Sources in the vlog

To cite sources effectively in academic speaking, you can use the following common phrases:

- At a conference in [month/year]**,** X demonstrated that mnemonic imagery helped learners retain vocabulary sets.

- In a study published in [journal/year]**,** spaced repetition improved recall over time.

- In a survey published in [year], …'s results showed ...

- In [year], … proved that ...

- According to …, ...

- As … says/explains / reports, ...

- Data from …'s website support ...

- At a conference on [date], … explained how ...

Quick source notecard format (for preparation)

Author, Year, Title, Source Type, Key Finding (1 line), How I'll use it in the video.

<u>Project Block 5</u> <u>Draft storyline ideas with evidence</u>

1. Work in pairs. Decide which of the work in your Project Blocks you want to include in your vlog. Think about:

1. What would be interesting to listeners?

2. How many parts to the vlog do you want?

3. What would be a good order for the parts?

2. Write a brief summary of each memory technique, defending facts and using elements of an explanatory synthesis essay. Outline the stages for each technique. Decide, plan, and incorporate visual aids and examples to effectively demonstrate the techniques.

Project diary – My storylines

Technique	*Stages*	*Summary*
Memory technique (mnemonic) 1	Stage 1 Stage 2 Stage 3 Stage 4 Stage 5	
Technique 2 …		
Technique 3 …		

Step 3: Make up a plan for a vlog

<u>Project Block 6:</u> <u>Share and review ideas from Project Blocks 2-5.</u>

1. Discuss in pairs.

1. What vlogs do you watch/listen to? What do you like about them?

2. Which of the work in the Project Blocks do you think would be the most interesting and informative to include in a vlog?

2. Read *the learning strategy*. Start to plan your video using a Project diary. Remember, it should be no more than 5 minutes. When planning a learning vlog, follow a series of questions to clarify your objectives and how you plan to achieve them.

Learning strategy 6 - Educational vlogging focus –

Incorporating mystery/surprise / dynamic atmosphere and researched benefits

- When you are telling a short story through video, try to create an element of mystery so that the end has a 'twist'. For instance, open with a puzzle: flash 10 new vocabulary items, hide them, then ask, "How many can you recall? Stay to the end, we'll test again."

- Begin in a way that will mean the viewer wants to continue watching to clarify doubts.

- Add images to intrigue the viewer and create a dynamic educational atmosphere. Visual intrigue: before/after memory score meter.

- Encourage active learning elements, such as prompts for viewers to solidify their understanding. Reveal twist: Show viewers that they now recall all 10 words after using the mnemonic and tying it back to research.

Project diary – Plan the vlog

1) Who is your target audience? (consider age, English proficiency level, educational background)	
2) What specific memory challenges do they face when learning English?	
3) What are your objectives? What do you want viewers to *know/be able to do/or feel motivated to try* after watching this vlog?	

Essay Link 1: Draft a working thesis answering: *What can improve memory performance?*	
4) Look back at your Project Block 3. Does your storyline follow the 5 stages? If not, what's missing?	
5) How do you structure the vlog to keep it digestible and engaging? a) Do you hook viewers with a mini-mystery? b) Does the story contain some suspense to make the vlog more compelling? c) Have you got an idea for a twist or reveal near the end?	
6) What visuals, countdowns, and on-screen prompts will you use to explain and demonstrate each memory technique? What active learning tasks will you incorporate so viewers can practice during the video?	
Essay Link 2: Which of these techniques will become your essay body paragraph topics?	
7) Do you use information from Project Builder 4? Are there experts or research studies you can reference to add credibility to the information you're providing? Are you supporting your claims with reliable sources (authors, years, and relevance)? What additional reliable sources can you provide for viewers who want to explore the topic further?	
Essay Link 3**:** List sources + key findings for each technique; note overlaps/contrasts among sources.	
Essay Link 4: Convert essay takeaways into brief practical applications in the vlog.	

Step 4: Revise and assess the script of the vlog

<u>**Project Block 7.** Write the script</u>

1. Write the script for any parts of your vlog that you need to. Use the Key phrases to help you.

Key phrases: Making a vlog		
Starting a vlog	Linking between parts	Ending a vlog
• Welcome to ..., with your hosts ... and ... • Today we're talking about ... • We're going to start with ...	• Now we're going to talk about ... • The next part of the show is about ...	• Well, that's all we have time for this week. • Please subscribe if you enjoyed the show. Thanks for listening, everyone!

2. Practise the different parts of your vlog.

3. Study the six-criteria assessment for the vlog.

<table>
<tr><td colspan="4">1) Vlog composition and design evaluation</td></tr>
<tr><td>Composition and structure</td><td>Design and visual appeal</td><td>Content completeness and informativeness</td><td>Argumentation and persuasiveness</td></tr>
<tr><td colspan="4">2)Text quality assessment</td></tr>
<tr><td>Content depth and problem disclosure</td><td colspan="2">Coherence and consistency</td><td>Language and editorial quality</td></tr>
<tr><td colspan="4">3)Project and research methodologies evaluation</td></tr>
<tr><td colspan="2">Professional and pedagogical problem-solving strategies</td><td colspan="2">Information and research methods</td></tr>
<tr><td colspan="4">4) Presentation quality assessment</td></tr>
<tr><td colspan="2">Content impact</td><td colspan="2">Audience engagement</td></tr>
<tr><td colspan="4">5)Project contribution evaluation</td></tr>
<tr><td colspan="2">Relevance and originality</td><td colspan="2">Creativity and task quality</td></tr>
<tr><td colspan="4">6) Speech and learning skills development assessment</td></tr>
<tr><td>Communication skills</td><td colspan="2">Public speaking skills</td><td>Personal development</td></tr>
<tr><td></td><td colspan="2"></td><td></td></tr>
</table>

4. Check that you consider the criteria and that the script is consistent and logical. Add short actions to the linguistic and speech registers. Edit grammar, vocabulary (adjectives to create an educational atmosphere), and the style of language of your script, if necessary.

Project diary– The script of the vlog

Vlog composition and design – Key moments and their order
Text quality
Project and research methodology
Presentation quality
Project contribution
Speech and learning skills

Step 5: Follow the plan, record the vlog, and show it to the target audience

Project Block 8. Film a professionally focused vlog sharing the best memory techniques for learning foreign languages.

1. Make a recording and follow the plan.

1. Find a quiet space to record your podcast.
2. Record each part of your podcast separately.
3. Try not to worry about making mistakes.
4. Use software to edit your audio and combine the different parts into one audio file.
5. If possible, add interests to your vlog by using music.
6. Save the file in a safe place!

2. Use the planner to check that your vlog is ready. If necessary, edit it.

Project diary – My revision planner

1. What are you going to use for filming the video?	
2. When are you going to do it?	
3. When will the setting be?	
4. Do you need to film in a realistic setting or use props to create the setting?	
5. What are the key moments of the video? How can you make them stand out?	
6. What type of 'shot' (picture) throughout the video do you use to keep viewers interested? 1. a wide shot: this shows the whole scene; 2. a close-up shot: this usually shows only one thing or one person; 3. a split-screen shot: this can show a close-up of more than one thing ot person at the same time.	
7. What software do you need?	
8. Do you check the length of the script that has been allowed? Do you time yourself? How long does each part of the vlog take? Do you add your estimates of timing to each part?	
9. Do you read through the script, including any time for action to take place?	
10. Do you edit if it seems to be too long?	
11. Do you use some effects (words on the screen) to replace longer parts and make sure you stay within your time?	
12. What is actual runtime after edit: ________. Target runtime (max 5 minutes) Did pacing feel too fast, too slow, or about right?	
13. Do you close by reviewing the main takeaways and inviting viewers to try the techniques in real study sessions?	
14. Do you ask viewers to share results and tips so the community learns together?	

Step 6: Reflection and peer-assessment questionnaire

1. Think about your vlog in the following aspects and evaluate them. Circle or highlight the score that best matches your work (1 = needs major improvement; 5 = excellent).

Creativity	The vlog presents information in a visually clear and inventive way. Graphics, examples, and storytelling choices effectively highlight the key points.	1 2 3 4 5
Digital literacy	I can select and use appropriate effects, digital tools, apps, or websites to convey information. Viewer analytics and comments show the audience reacted as I expected.	1 2 3 4 5
Credibility	The project draws on well-researched benefits and reliable sources. Citations are transparent, and the content engages the audience while maintaining their trust.	1 2 3 4 5
Critical thinking	I evaluate the quality of information, detect bias, and compare multiple viewpoints before including them. Arguments in the vlog are logical and evidence-based; reflections show how I might improve.	1 2 3 4 5
Problem-solving skills	I identify technical or communication challenges during planning, filming, and editing, then test and apply solutions (e.g., fixing audio issues, reorganising content flow). Time and resources were managed efficiently.	1 2 3 4 5

2. Answer the questions.

Your takeaway box	
What did you learn during the research process that was unexpected?	
Are you pleased with your vlog? If yes, why?	
What would you do differently if you were to complete this project again?	
Which skills do you feel you developed or strengthened while creating and presenting your vlog?	
Are there any technical or performance aspects you would like to improve for future vlogs?	

What did you learn about yourself while working on this project?	
Did you encounter any challenges while creating your vlog, and how did you overcome them?	

3. Watch/listen to your groupmates' vlogs. Complete the table entry for dimension 1–6. Circle or highlight the score that best matches the work (1 = needs major improvement; 5 = excellent).

Vlog title and presenter	1. Language (accuracy, range, pronunciation, discourse organization 1 2 3 4 5	2. Pedagogical clarity (the explanation teachable, scaffolds are used) 1 2 3 4 5	3. STEM accuracy (concept correctness, data use, safety notes) 1 2 3 4 5	4. New insight I gained from the vlog 1 2 3 4 5	5. Most surprising/engaging moment 1 2 3 4 5	6. Question / suggestion that made me think 1 2 3 4 5

The theoretical and methodological considerations outlined above served as the foundation for designing a structured learning sequence centred on the STEAM-oriented learning vlog (SOLV). This pedagogical design operationalises the key principles of project-based and inquiry-driven learning within a competence-based framework, translating them into step-by-step classroom activities that integrate language development, digital literacy, and reflective practice. To evaluate how effectively this design supports the development of professionally oriented communicative competence in pre-service English teachers, a pilot implementation was conducted. The following section presents the structure of this implementation, its methodological design, and the empirical results obtained.

Pilot Implementation: Methods and Findings

Design: A semester-length, two-arm cluster-randomized pilot study examined the effectiveness of SOLV projects in an English practical course for pre-service English teachers. Four groups were randomly assigned at the group level to one of two arms: Experimental (English practical course with a SOLV project) or Control (English practical course with a standard research/presentation project without vlogging. Pre– and post- within-group changes and between-group differences were analyzed.

Setting and participants: The study was conducted at Kyiv National Linguistic University. Participants were 60 pre-service English teachers enrolled in the English practical course (four parallel groups of 15 students each).

Intervention: Experimental Over 5–6 weeks embedded in the regular course, students completed a SOLV sequence ("Boost Your Memory") integrating professionally oriented communicative competence (reading, writing, speaking, listening, mediation) with STEAM-framed content and digital production. The scaffold included: 1. driving question and topic scoping (memory techniques for language learning); 2. multisource reading and evidence building; 3 script/storyboard drafting and peer revision; 4. filming and editing (mobile apps such as InShot/FilmoraGo permitted); 5. publication on the group LMS, followed by audience feedback and guided reflection. Teacher support (brief workshops/consultations) was provided within scheduled class hours; no separate methodology course was involved.

Control-group students completed a standard project aligned with the same language objectives (topic research, in-class oral presentation, and a short written brief) without vlogging, video production, or explicit STEAM framing. They received routine instructor feedback typical of the English practical course.

Course-embedded measures: All instruments were administered pre- (Week 1) and post- (Week 6): POCC proxy rubric (0–20). Course-aligned indicators of professionally oriented communicative competence, scored on a teaching-like task (e.g., 3–5-minute explainer/micro-teaching/vlog narration). Five criteria × 0–4: (1) Linguistic accuracy, range, and pronunciation;

(2) Discourse organisation; (3) Audience adaptation and clarity; (4) Mediation moves (rephrasing, exemplifying, linking visuals/data); (5) Professional and sociocultural register. Totals: 0–5 Minimal; 6–10 Developing; 11–15 Proficient; 16–20 Advanced. Note: A separate Mediation task (0–20) is used as convergent evidence for the POCC mediation subscore and is not added to the POCC total. Speaking performance (0–20): 3/5-minute monologic task scored with the course rubric (fluency, accuracy, pronunciation, discourse organization).

Mediation task (0–20). “Explain-it-like-I’m-a-beginner”: transform a ~150-word technical paragraph into learner-friendly language; rubric aligned to CEFR mediation descriptors (selection/simplification; paraphrase/explicitation; linking visuals/data; terminology management; coherence).

Digital-literacy self-efficacy. Ten-item Likert scale (1–5) covering planning, producing, editing, citing sources, and handling feedback in digital formats (internal consistency α estimated post hoc).

STEAM content and design quality (fidelity, Experimental arm only). Five-item presence checklist plus a quality rubric (5 × 0–4; total 0–20): (1) conceptual accuracy of science/tech content; (2) data representation & interpretation; (3) multimodal coherence (visuals–narration–captions alignment); (4) accessibility and safety/ethics (captions, legibility, audio, safety notes where relevant); (5) evidence and citation (transparency, recency, relevance). Used to document implementation quality, not as a learning outcome.

Engagement/reflection: brief six-item exit survey and a structured reflection prompt (qualitative). All rubrics and prompts were part of normal assessment in the English practical course and were used identically across groups (except that the experimental group performed the SOLV variant of the final task).

Procedure and timeline:

Week 1 (baseline & allocation). Baseline assessments for both arms included the POCC proxy (0–20), speaking (0–20), mediation task (0–20), and digital-literacy self-efficacy (10-item

Likert). Cluster randomisation at the class level by an administrator independent of instruction; allocation revealed after baseline. Both arms received identical syllabus, contact time, topics, and deadlines. (For the SOLV workflow, see Intervention.)

Weeks 1–2 (planning). Both arms: topic scoping and source gathering. Experimental classes commenced SOLV planning consistent with the Intervention specification; control classes planned a standard research/presentation project. Weekly fidelity checks recorded time-on-task and (for Experimental only) presence of required STEAM elements.

Weeks 3–4 (development). Experimental: continued SOLV development per Intervention (scripting/production stages). Control: prepared slide-based presentations. Learning-strategy evidence (planning logs, version history) was collected in both arms. Instructor coaching minutes were held equal across arms.

Week 5 (delivery & peer feedback). Experimental: SOLVs published on the LMS with rubric-aligned peer feedback. Control: live slide presentations with the same peer-feedback prompts. For research scoring, videos were anonymized where requested; only course instructors had access to identifiable files for grading.

Week 6 (reflection). Post-assessments were repeated for all measures; the exit survey and structured reflection were completed. Contamination control: no cross-arm sharing of artefacts until all post-tests were finished.

To estimate positive change on each outcome, we calculated pre–post differences (Post-Pre) and expressed gains relative to each scale's total range. Figure 1 visualises the results. The Experimental group shows consistent, substantive gains across all indicators, whereas the Control group shows only small changes. The largest improvements are observed for the POCC composite and for speech competence, especially mediation, followed by oral production**,** learning-strategic competence**,** and sociocultural competence**.** Linguistic competence, including phonetic, lexical, and grammatical subcompetences, also rose appreciably. Digital-literacy self-efficacy rose meaningfully in the Experimental arm. By contrast, the Control arm exhibited only modest, non-significant movement. Overall, the pattern in Figure 1 supports the effectiveness of SOLVs in strengthening POCC and related competencies.

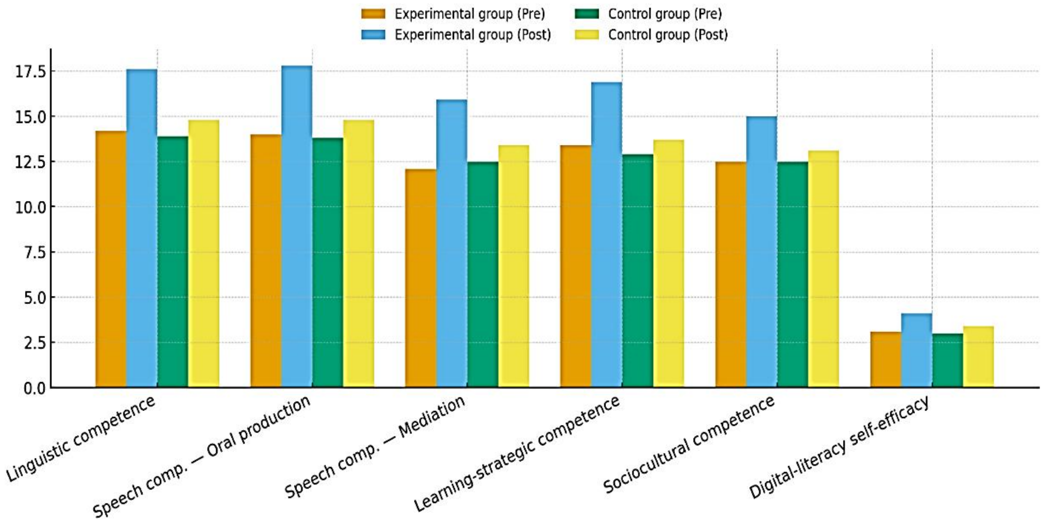


Figure 1. Effect of STEAM-oriented learning vlogs on POCC and related outcomes: Experimental vs. control, pre- and post-means. Source: developed by the author

The findings support the hypothesis that SOLV projects are an effective vehicle for developing POCC. Gains were most evident in linguistic competence (clearer pronunciation; more precise lexico-grammar) and speech competence, both in oral production (greater fluency and discourse control) and mediation (clearer paraphrase, explicitation, and terminology management for non-experts). The vlog workflow also strengthened learning and strategic competence through more systematic planning, monitoring, and revision, and improved sociocultural competence by utilizing audience-aware register choices and inclusive presentation. Digital-literacy self-efficacy rose as a transversal enabler of these outcomes. Importantly, higher STEAM content and design quality within the Experimental arm were associated with larger mediation gains, suggesting a fidelity–impact link. By combining inquiry-driven, multimodal tasks with structured reflection and peer assessment, the intervention advanced language development while cultivating the broader competencies expected of contemporary language professionals.

Conclusions

This study provides initial evidence that SOLVs are a viable, high-impact vehicle for developing POCC in pre-service English teachers. Pilot evidence from a cluster-randomised, pre–post comparison with a business-as-usual project supports these claims: the SOLV groups outperformed controls on POCC-aligned indicators, speaking, mediation, and digital-literacy self-efficacy, with the largest gains in linguistic accuracy/pronunciation, oral discourse control, and mediation moves. Moreover, higher STEAM content/design quality co-occurred with stronger mediation gains, suggesting that fidelity to the STEAM brief (conceptual accuracy, data representation, multimodal coherence, accessibility, transparent citation) is pedagogically consequential rather than decorative. Overall, SOLV integrates authentic STEAM content with digital pedagogy, advancing POCC and 21st-century teacher capacities in tandem. Students are not only learning English; they are learning to teach through English. Preliminary practicum observations suggest that SOLV skills are transferable to real classroom settings.

This was a short, single-institution pilot with intact classes and course-embedded measures. Next, a stratified multi-site cluster trial (encompassing diverse universities) with a longer follow-up should test durability and classroom transfer, and assess whether STEAM design quality mediates language gains. Further work will design and evaluate targeted activities to deepen pre-service teachers' POCC in blended higher-education environments.

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Chapter 4

INTEGRATION OF STEM/STEAM INTO SPECIALIZED EDUCATION AND SUSTAINABLE DEVELOPMENT

4.1. The Evolving Role of the Foreign Language Teacher in Integrating the STEAM Approach Into Military Education

Anna Zhukova, Mariia Halchenkova, Yaryna Dziuba, Svitlana Demikhova

***Abstract**. The section explores the evolving role of the foreign language teacher in integrating the STEAM approach into the training of military specialists. It argues that language instruction in military education should move beyond isolated linguistic practice toward interdisciplinary learning that connects linguistic, technical, and professional competencies. The study identifies the core professional functions of the language teacher (educational, constructive, research, organizational, and evaluative) and explains how they transform in a STEAM-based environment. Particular attention is paid to the integration of language and professional disciplines, which fosters communicative, analytical, and decision-making skills essential for modern officers. Drawing on Canadian experience, the paper illustrates how project-oriented and technology-enhanced learning models can strengthen teamwork, intercultural competence, and professional adaptability. The survey conducted among cadets of the Hetman Petro Sahaidachnyi National Army Academy confirms the relevance of the STEAM approach and highlights the teacher's role as an interdisciplinary facilitator who bridges linguistic and technical domains. The findings can inform the design of in-service training programs for foreign language teachers and contribute to the modernization of Ukraine's military education system.*

***Keywords**: STEAM education, military education, interdisciplinary learning, foreign language teacher, Canada–Ukraine cooperation.*

Introduction

Currently, the military education system is undergoing significant transformations in response to the challenges of a full-

DOI: 10.31110/STEM-CaUk-4.1

scale war, the dynamic development of technologies, and globalization processes. In such circumstances, there is a growing need to train specialists capable of interdisciplinary thinking, teamwork, and effective communication in situations of stress and uncertainty. One of the promising areas for modernizing the educational process is the introduction of the STEAM approach (science, technology, engineering, art, and mathematics), which ensures the integration of different fields of knowledge and promotes critical and creative thinking. In this context, the role of the foreign language teacher is of particular importance, as they not only provide language training but also act as mediators of interdisciplinary dialogue, developing the communicative competence of military personnel in professional situations. Studying the experience of Canada as a country with a developed system of military training based on STEAM education is relevant for updating the Ukrainian model of language teaching in higher military educational institutions.

In recent years, the problems of STEM education research have become increasingly relevant, and modern Ukrainian and foreign researchers are engaged in their development. Thus, the problem of implementing the STEM approach in educational institutions of various levels and profiles is reflected in the works of scholars such as O. Hrybiuk, L. Hryzun, N. Morse, V. Sipiy, O. Stryzhak, and I. Chernetskyi, among others. The studies of foreign scientists are of great interest, as noted by J. Confrey, M. Harrison, A. House, D. Langdon, B. Means, N. Morel, and E. Peters-Burton, among others. However, the issue of using the STEAM approach in military education remains poorly understood and therefore requires generalization and detailed study.

The purpose of this paper is to analyze the possibilities and benefits of implementing the STEAM approach in the training of military specialists, to outline the role of the foreign language teacher in an interdisciplinary learning environment, and to explore the practical aspects of adapting Canadian experience to Ukrainian realities.

The study employed a set of general scientific and specialized methods, which enabled a comprehensive characterization of the specifics of implementing the STEM approach in military education in Ukraine and its importance for the formation of highly qualified military personnel. The methodological approach was based on a systematic analysis, which allowed us to consider STEM education as an integrated system with an interdisciplinary structure that includes natural, technical, engineering, and mathematical components. The application of the structural-functional approach enabled the identification of key functions of the STEAM approach in enhancing the human capital development of the Armed Forces of Ukraine, increasing competitiveness, and strengthening the state's innovative potential. In addition, a comparative analysis of modern scientific publications by Ukrainian scientists was conducted, which enabled us to summarize theoretical approaches to defining the essence of the STEAM approach and its key advantages, as well as to analyze the challenges associated with its implementation in practice.

Research Results

Implementation of STEAM education is becoming increasingly relevant in the modern world, as this learning model not only promotes critical thinking and creativity but also prepares students for the challenges of the future. STEM education, which integrates science, technology, engineering, mathematics, and the arts, is a key component of the modern educational process. The introduction of STEAM education is strategically important for the future development of society, particularly in the context of the Fourth Industrial Revolution and globalization. STEAM education is a comprehensive educational approach that integrates science, technology, engineering, arts, and mathematics to develop students' comprehensive, analytical, creative, and practical skills. This methodology is designed to prepare students to solve real-world problems through interdisciplinary learning that fosters innovation, critical thinking, and teamwork (Bocharova, 2024, p. 389). STEAM education focuses on the development of creativity and an innovative approach, combining technical and humanitarian knowledge to achieve comprehensive student development.

As N. Matsai notes, the STEAM approach makes it possible to develop critical, practically oriented thinking in students, flexibility in perceiving and understanding new information, a different view of the problem, the ability to defend their opinions; it will allow them to develop the ability to research, analyse, experiment and teach them to successfully combine the acquired knowledge to solve practical problems and further use it in their professional activities (Matsai & Gubska, 2023, p. 45).

Furthermore, the STEM approach is based on several key principles. The principles of STEM education form a system of provisions that serve as the basis for organizing the cognitive activity of participants in the educational process using the STEM approach (Fig. 1).

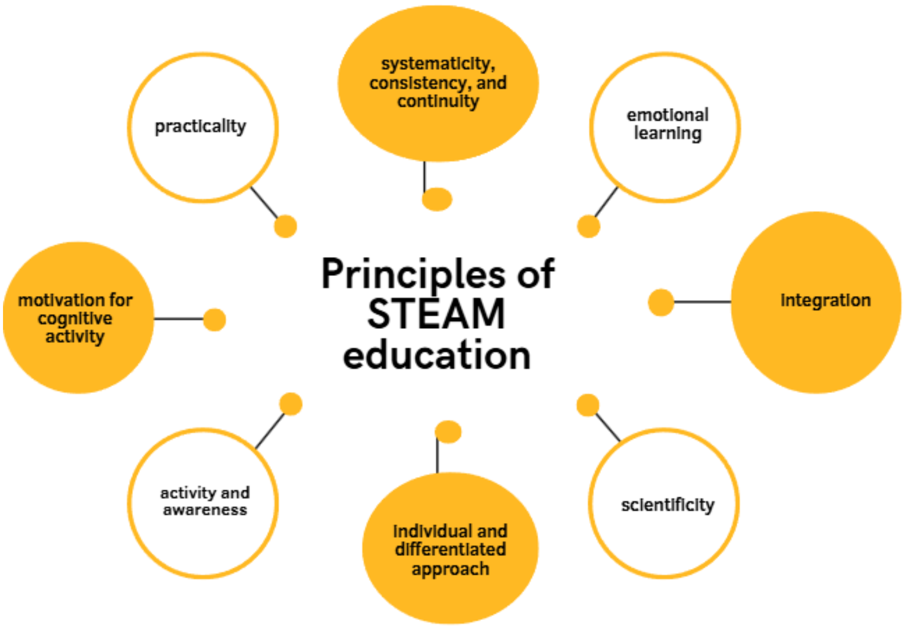

Figure 1. Principles of STEM education

The principle of integration. The essence of integration is to combine individual elements, characteristics, and functions into a single holistic system, which, as a result, acquires new integrative properties. In the context of STEM education, integration covers not only the combination of knowledge from different fields - physics, mathematics, geography, biology, ecology, and art - but also the introduction of a whole range of forms and methods of teaching that contribute to the effective acquisition of this knowledge and the development of interdisciplinary thinking.

The principle of science involves establishing cause-and-effect relationships based on reliable, proven knowledge that corresponds to the current level of science and technology. In STEM education, it is essential that students form such connections independently, integrating knowledge from various fields and utilizing modern, innovative methods of acquisition.

The principle of practicality (linking learning to real life) focuses the educational process on the use of examples from everyday life that contribute to the understanding of natural laws and phenomena through direct practice. The STEAM approach is based on practice-oriented forms and methods that enable you to learn about the world around you through active work.

The principle of consistency, systematicity, and continuity is based on a holistic perception of phenomena and processes, taking into account the interconnections between all elements of the system. STEM education implements this principle through a continuous and consistent learning process that begins in childhood and continues throughout life. This provides a multi-level understanding of objects and phenomena in their dynamics, interaction, and development.

The principle of activity and awareness encourages students to learn independently and solve problem situations. In STEM education, this principle is implemented by engaging participants in conscious activity, which results in the formation of a reasoned and effective approach to solving problems.

The principle of motivation for cognitive activity involves maintaining an internal desire to learn, which can be supported by external factors. In the STEM approach, motivation is enhanced by raising topical issues that can improve the quality of life. This encourages the integration of knowledge from different fields and its practical application.

The principle of an individual and differentiated approach emphasizes independence, taking into account the individual characteristics and pace of development of each participant. In the context of STEM education, this is realized through independent research, choosing a personal learning trajectory, encouraging teamwork while maintaining personal activity and involvement in educational interactions.

The principle of emotional learning emphasizes the role of emotions in the cognitive process. The STEM approach is based on the practical solution of real-world problems that are of personal importance to participants. Emotional involvement in the process contributes to deeper learning, increased motivation, and the formation of a positive attitude towards learning (Postova, 2024, p. 140-141).

Importantly, the STEAM approach in the educational process is increasingly being implemented not only in civilian but also in military education. In the context of training military specialists, it enables the development of professional competencies, critical thinking, creativity, teamwork, and interdisciplinary interaction – qualities that are crucial in the modern combat environment. Currently, in the context of a full-scale war, STEM education should become the primary focus in updating innovative technologies within educational institutions, including those in the military, because modern technologies and military education are the primary factors capable of deterring the enemy.

The main advantages of using the STEAM approach in the training of military specialists are as follows:

1. Development of interdisciplinary thinking – STEAM integrates knowledge of science, technology, engineering, art, and mathematics, which enables military professionals to think systematically, consider tasks from different perspectives, and make informed decisions in the face of uncertainty.
2. Increasing the level of adaptability and creativity – by incorporating the artistic component of the STEAM approach, cadets develop creative thinking and the ability to solve tactical and strategic tasks in a non-standard way.
3. Preparation for a real interdisciplinary environment – the modern military environment requires knowledge not only of combat, but also of IT, cybersecurity, logistics, engineering, and psychology. STEAM provides an integrated approach to training such specialists.
4. Increasing the effectiveness of teamwork – STEAM education is focused on collaborative forms of learning, including group work, problem solving, and joint planning of operations, which is extremely important in the military profession.

5. The use of practice-oriented methods – project-based learning, simulations, and case studies helps develop decision-making skills in stressful situations, analytical thinking, and rapid response.
6. Development of digital literacy – through the use of technological tools (drones, geographic information systems, etc.), the STEAM approach develops digital competencies required in the modern man-made military environment.
7. Motivation to learn – STEAM increases the interest of cadets through relevant, integrated, and applied learning content that is directly related to their future professional activities.
8. Flexibility and innovation – this approach contributes to the formation of a new type of leader, open to innovation, ready for rapid change, and able to act effectively in the face of hybrid threats.

Today, national programs in STEM education are being actively implemented in countries around the world, including Australia, China, Great Britain, Israel, South Korea, Singapore, and the United States. They are based on a combination of interdisciplinary and project-based approaches, as evidenced by the widespread introduction of STEM subjects in the curricula of leading US universities. In the field of military management, the requirement for military professionals to be not only disciplined and responsible but also able to make effective management decisions, implement innovative approaches, and act effectively in conditions of high uncertainty is becoming increasingly important. This requires possession of modern digital competencies, basic technical knowledge, and skills in working with information technology. The application of an interdisciplinary approach, the creation of a digital educational environment and the possibility of developing their own STEM projects during professional training and advanced training, as well as the integration of educational robotics elements into the curricula of military universities, all contribute to: increasing the interest of military personnel in technical sciences and engineering; better mastery of technology-related disciplines; development of critical, innovative and creative thinking; formation of skills in solving practical problems and mastering the use of modern information technologies. As a result, this approach enables training military specialists who cannot only adapt to changes but also actively participate in creating technological solutions for performing service tasks (Prokopenko, 2022).

The current system of training military specialists in Canada implements a phased system that ensures continuous professional development throughout the entire service. A key feature of the training is the mandatory combination of higher education with military service, which enables more effective learning and the consolidation of new knowledge in practice. Officers of the Canadian Armed Forces, holding leadership positions, are responsible for the safety, welfare, and morale of their subordinates, as well as analytical work, planning, management, decision-making, and strategic recommendations. Canadian officer training is based on five areas: tactical training, education, leadership, self-development, and experience. These are the aspects that are emphasized in the career development of military personnel (Army in Canada, 2022).

This training format provides for a deeper understanding of the material and allows for immediate consolidation and application of the knowledge gained during service. During the course of service, the serviceman utilizes the relevant knowledge required to perform tasks in accordance with their new position. Given the hierarchical career development system in the Canadian military, it can be argued that a flexible, phased model of education is the most appropriate and effective approach. This relationship between education and career advancement has both advantages and limitations. On the one hand, the system stimulates continuous learning, development, and improvement of professional skills, while on the other hand, focusing on a specific future position narrows the serviceman's range of knowledge. At the same time, such specialized training allows one to achieve a high level of professionalism in the chosen field of activity (Voronin & Trishchun, 2022, p. 111).

In addition, Canada actively employs the STEAM approach in the training of officers and military specialists, as it enables the integration of technical, humanitarian, and managerial skills, which is particularly important within modern hybrid threats and the dynamic evolution of military technologies. Canada uses project-based learning, where cadets work on projects that integrate science, technology, engineering, arts, and mathematics. This approach implies that cadets not only acquire theoretical knowledge but also work on practical interdisciplinary projects that simulate real military tasks and situations that may arise during their service. Throughout the project activities, participants learn to apply modern technologies, analyze information, develop innovative technical solutions, work in teams, and communicate effectively, including in foreign languages. All of this helps develop critical and systematic thinking, leadership skills, and the ability to take a holistic approach to problem-solving, which is especially important in the rapidly evolving military technologies and the need for international cooperation.

As for foreign language instruction in the Canadian Armed Forces, the Foreign Language School is responsible for providing foreign language training to support the needs of the Armed Forces. The training is provided in three different programs, which are designed to meet the specific needs of the tasks and goals. The first is the basic program for learning foreign languages, which the national military agency aims to implement to train linguists, military diplomats and translators, as well as officers for international commissions, officers in charge of training internships (and a number of other specialists) with the knowledge of foreign languages to the extent that they can effectively solve their tasks. Today, there are five main courses that teach more than 30 foreign languages (Vorona et al., 2022, p. 45).

Another important area is the Combat Training Support Program, the main purpose of which is to teach officers from participating countries in the Partnership for Peace program English and French. This helps to achieve interoperability between armed forces during NATO operations, and also allows foreign military personnel to learn about the government, social features, culture, and organization of the Canadian Armed Forces. The courses are conducted for different categories of military personnel, varying in duration (10-17 weeks), international representation (from 4 to more than 13 countries), and participant numbers (from 40 to 200 people).

The third area is the second foreign language program. Its main goal is to provide the Canadian Armed Forces with a sufficient number of bilingual personnel (primarily English and

French), which is especially important in the context of the numerical reduction of the armed forces and the complexity of combat training and troop organization. As a rule, second language teaching is organized in linguistic centers subordinated to the command of a particular type of armed forces (Dyson, 2022).

A crucial role in this process is played by the foreign language teacher, whose contribution to interdisciplinary teaching is pivotal. In the context of globalization and active international cooperation (in particular, within the framework of Canada-Ukraine military partnership programs), a high level of communicative competence is becoming a prerequisite for effective interaction with foreign colleagues, participation in international exercises, joint operations, and access to modern military technologies and knowledge. A foreign language teacher in the STEAM approach is not limited to traditional grammar and vocabulary teaching; instead, it integrates language training with technical, engineering, scientific, and management disciplines. This is achieved through the use of project-oriented tasks, modelling real military situations, and the use of digital technologies and artificial intelligence tools to develop intercultural communication and critical thinking skills.

In our opinion, the foreign language teacher in the interdisciplinary training of military specialists plays a multifunctional role that extends beyond the traditional teaching of grammar and vocabulary. Firstly, it is worth noting that the teacher develops students' foreign language skills necessary for participation in international military operations, cooperation within NATO, and the exchange of experiences with foreign colleagues, including the development of oral and written communication skills, negotiation, report writing, and military documentation. In the STEAM approach, the foreign language teacher collaborates with instructors in military tactics, cybersecurity, engineering, and medicine to create learning situations where language is used in a practical context. These can include role-playing games, simulations of military operations, and team projects that combine linguistic and professional competencies.

In addition, given that the military is often involved in peacekeeping missions and international operations, a foreign language teacher helps to acquire knowledge of the cultural characteristics of partner countries, which contributes to effective communication, reducing conflict situations, and strengthening mutual understanding between allies. Interdisciplinary training involves analyzing real-life military scenarios, which encourages students not only to reproduce language structures but also to think strategically, justify decisions, argue a position in a foreign language, and more. In addition, in Canada and, gradually, in Ukraine, teachers are actively using artificial intelligence, online simulators, language simulators, and interactive platforms to develop teamwork skills and improve learning efficiency.

The teacher is not only a source of knowledge but also a facilitator who supports students, organizes the educational process, and motivates them to achieve their goals (Hutsul, 2024). The foreign language teacher also serves as a mentor, helping military personnel overcome the language barrier, lack of confidence in communication, and adapt to a multicultural environment, while enhancing their stress resistance in international military missions.

We believe that a foreign language teacher in interdisciplinary education performs a number of important functions, including:

- diagnostic
- prognostic;
- constructive and designing;
- informative and explanatory;
- organizational;
- analytical and evaluation;
- communicative and stimulating;
- research and creative (Fig. 2).

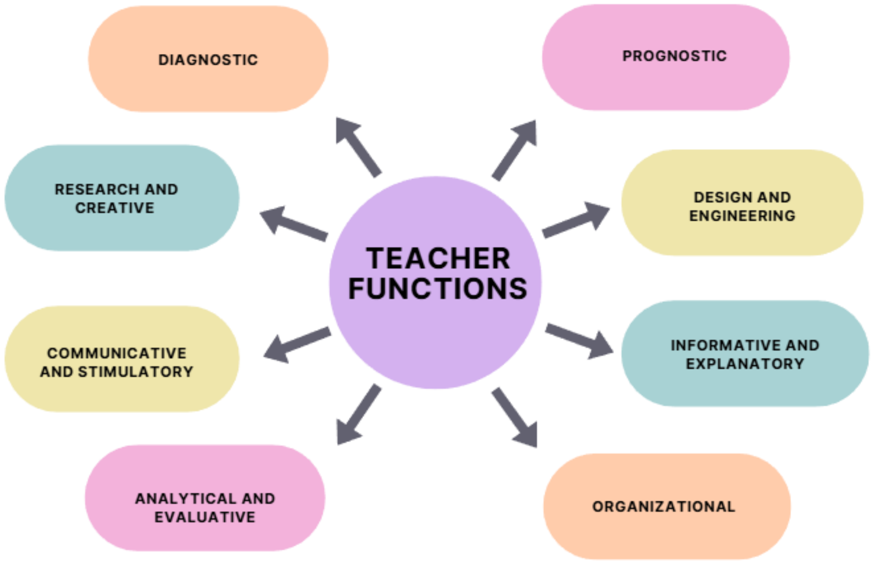

Figure 2. Functions of a foreign language teacher in interdisciplinary teaching

Thus, the diagnostic function involves recognizing and determining the knowledge, skills, and development skills of military specialists, their language competencies, strengths, and weaknesses, which makes it possible to qualitatively analyze the educational process, identify factors that contribute to the successful implementation of interdisciplinary learning, and determine the needs and directions of further work. The teacher should be observant in identifying individual abilities of military education students.

The prognostic function is associated with predicting the results of one's own activities focused on specific goals and objectives, predicting possible learning outcomes, developing strategies for speech skills, and integrating them with other disciplines. The prognostic function also implies a vision of the traits of military specialists that can be formed over a certain period of time.

The constructive and design function is closely related to the prognostic function and consists of the selection and organization of the content of educational work, in designing the activities of military specialists, taking into account their needs, as well as their own future activities, in the ability to reorient the goals and content of education to specific tasks of interdisciplinary learning.

This function is realized through the development of curricula, tasks, and methodological materials designed to achieve the goals of interdisciplinary education.

The informative and explanatory function is related not only to the ability to present educational information in an accessible way but also to the skills of research, professional activity, and effective interdisciplinary learning. A foreign language teacher acts as a carrier of scientific, ideological, moral, and ethical information, while also providing new knowledge, explanations of complex linguistic phenomena, and ways of applying them in a professional and interdisciplinary context.

The organizational function is determined by the ability to engage military professionals in various activities and stimulate their activity. To achieve this, the teacher must be able to plan joint work, distribute tasks effectively, develop initiative and interest in learning a foreign language, and create a sense of need for knowledge. In addition, the organizational function is to streamline the activities of military specialists in foreign language classes and create favorable conditions for their active participation in the educational process.

The analytical and evaluative function is the ability of the teacher to analyze and evaluate the results of the educational process, identify achievements and shortcomings, compare their own work with that of colleagues, and seek ways to improve and increase the effectiveness of interdisciplinary learning. The analytical and evaluative function also involves systematic monitoring and assessment of military specialists' performance, analysis of their work, and making adjustments to curricula.

The communicative and stimulating function involves the ability to communicate, establish friendly relations, and encourage students to engage in active interdisciplinary learning by example. This function is designed to maintain motivation to learn, stimulate speech interaction, and foster a positive emotional climate.

The research and creative function is associated with the creative application of well-established pedagogical and methodological ideas in specific conditions of interdisciplinary learning, determining individual approaches to professional development, continuous improvement of teaching methods, the introduction of innovations, and the development of creative abilities in both teachers and students.

In addition, we can distinguish the following professional functions of a foreign language teacher in interdisciplinary teaching:

- educational and pedagogical (teacher);
- constructive (course designer and materials provider);
- researcher;
- organizational (collaborator);
- evaluator (Fig. 3).

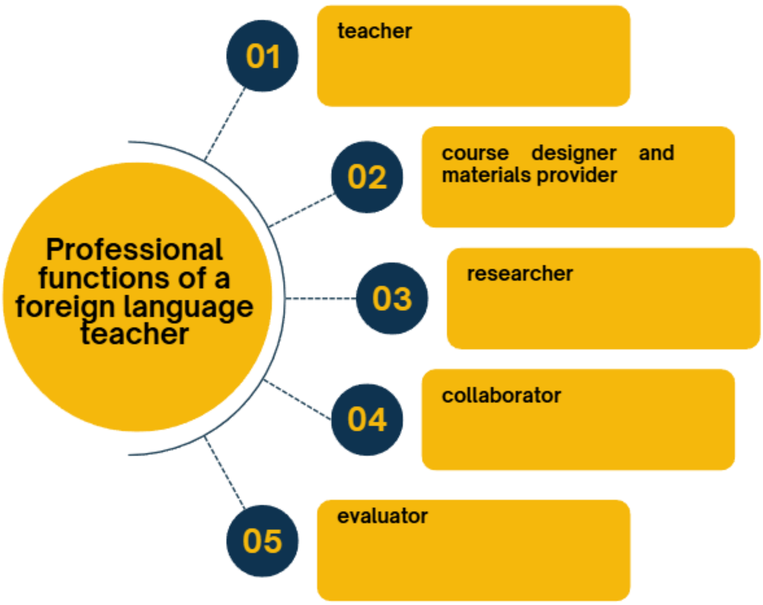

Figure 3. Professional functions of a foreign language teacher in interdisciplinary teaching

First of all, a foreign language teacher in interdisciplinary teaching is a philologist, a specialist in teaching a foreign language, whose main task is to form and develop students' foreign language communicative competence in oral and written forms, as well as practical foreign language skills in various types of speech activities, including in professional situations. The primary purpose of the teacher is to foster genuine, authentic communication in the classroom, drawing on the professional knowledge of military education students, and to prepare them for effective communication in a foreign language in both oral and written forms within their future specialty. At the same time, the teacher should always show interest in the professional sphere of students, be able to listen attentively, and demonstrate a desire to develop.

The constructive function of the teacher is related to the provision of educational material and the development of the discipline's course. The provision of teaching materials is not only about selecting the right textbook and supplementary materials, but also about tailoring them to the learning needs of both the entire group of students and each individual, taking into account the specific characteristics of the educational institution and the level of language proficiency. Often, existing textbooks fail to meet the needs of military education students, the curriculum requirements, and the specifics of related disciplines. That is why the teacher must develop methodological recommendations, teaching aids, and study guides on their own to align them with the learning needs of a particular group and adapt them to the requirements of related disciplines. To develop an interdisciplinary training program, the teacher analyzes the needs of military education students, identifies the goals to be achieved at the end of the course, and determines the competencies – both linguistic and professional – that need to be developed in students.

A foreign language teacher in interdisciplinary teaching should also be a researcher to meet the needs of military education students. First, they should research their goals and needs to develop the interdisciplinary course program and design the teaching materials. In addition, the instructor should be willing to learn and improve throughout their life, including participating in international scientific and practical conferences and seminars, publishing in professional journals, attending advanced training courses, taking classes from other instructors, sharing experiences with colleagues, and engaging in self-education. For the successful implementation of this function, it is necessary to create appropriate conditions, including free access to information resources, the latest research in the field of military education, and the teaching of foreign languages.

The organizational function of the teacher is to implement the ability to organize learning activities for students, creating conditions for achieving the desired results. To meet the learning needs of military professionals, teachers should work closely with those of related disciplines. This can be a regular form of cooperation in which the foreign language teacher receives information about the course program, its purpose, structure, or tasks that students will perform in their professional environment. The most effective cooperation occurs when a foreign language teacher and teachers of related disciplines consult with each other. In addition, the coordination of interdisciplinary projects and the creation of conditions for active student interaction in the learning process. At the same time, the foreign language teacher acts only as a consultant, a partner who helps military specialists develop the knowledge, skills, and abilities necessary for professional foreign language communication.

In the course of their professional activity, foreign language teachers in interdisciplinary education are involved in various types of assessment, including the evaluation of the achievements of military specialists, self-assessment of their own activities, and evaluation of the effectiveness of the course and teaching materials. The assessment of military specialists' achievements should be conducted both during and at the end of the course. The effectiveness of the course and its teaching materials should be evaluated during the course, at the end of the course, and after the course has concluded. This evaluation is very important for the instructor, as they often develop the course and learning materials independently. A vocationally oriented course is unique because it is impossible to create a single course that would meet the needs of all language learners. Thus, ongoing assessment is a crucial factor in creating a successful foreign language course in interdisciplinary learning, as it helps adjust learning strategies and maintain motivation for further development.

Thus, we agree with the researchers N. V. Shvets and O. V. Shvets that the role of a foreign language teacher in interdisciplinary teaching is key, as it is the teacher who acts as a facilitator of the integration of knowledge from different fields, motivates students to think comprehensively, and creates conditions for active interaction between disciplines. A foreign language teacher must not only have deep professional knowledge but also be open to new teaching methods, including project work, team discussions, case studies, and the use of digital tools. He organizes the educational process in such a way that students learn to apply theoretical concepts in practice, analyze interdisciplinary problems, and develop critical thinking. In addition, the teacher supports the development of communication and technological competencies, creating a favorable environment for collaboration and self-development, which is the basis for forming a competent and adaptive military specialist in modern conditions (Shvets, 2025, p. 280).

Therefore, in interdisciplinary teaching, it is crucial that a foreign language teacher continually improves their professional skills. The effectiveness of integrating the language component into other fields of knowledge depends on the teacher's competence. They must be familiar not only with the methods of language teaching but also with the content of related disciplines in order to adapt the material to the professional needs of students of higher military education. This implies the ability to select authentic texts, create communication tasks that reflect real-life situations in the relevant field, and develop students' skills in using language as a tool for cognition and professional activity. Continuous professional development, participation in seminars, workshops, and scientific and practical conferences, as well as collaboration with colleagues from other specialties, contribute to the enrichment of the teacher's methodological arsenal. This approach enables learning to be more meaningful, motivating, and focused on achieving both academic and practical outcomes.

In implementing an interdisciplinary approach, teachers from different disciplines should familiarize themselves with the content of each other's programs in advance. When developing curricula, all teachers should work together in the same direction. The purpose of such cooperation should be a single integrated program in a particular specialty, which will enhance the gradualness of learning, expand the scope of the acquired knowledge; facilitate the acquisition of deep theoretical and special professional knowledge by students; eliminate unnecessary duplication of educational material, i.e. save class time for studying material in a special discipline and reduce the burden on the student.

Interdisciplinarity is one of the distinct features of the present and the future of research and development in higher education. The interdisciplinary approach, in a broad sense, and scientific understanding are innovative trends, but at the same time, a task that can only be solved through the purposeful work and interaction of all participants in the educational process (Hnezdilova, 2023). In other words, the teacher's work in implementing an interdisciplinary approach should focus on creating a unified system of knowledge, skills, and abilities for military education students that is consistent in content and structure. At the current stage of development of the system of training military specialists, the interdisciplinary approach can become a catalyst for the educational process in higher military education institutions, provide comprehensive and thorough preparation of future military personnel for professional activities, as it covers a wide range of issues: from the acquisition of theoretical knowledge and the development of practical skills and abilities to apply them to the formation of personal and professional outlook.

Through interdisciplinary training, military professionals learn to effectively use foreign languages to work with technical documentation, manage military systems, conduct negotiations, and participate in analytical and command and control processes. The Canadian experience demonstrates that integrating language education with engineering, technical, and research training enables a high level of adaptability and professional mobility among military personnel. For Ukraine, this approach is promising, as it contributes to the modernization of military education and the training of competitive officers capable of operating in uncertain conditions, communicating effectively, and implementing innovative solutions in the defense sector.

The advantages of interdisciplinary education lie in its ability to form a holistic view of complex phenomena and processes, develop students' critical thinking and analytical skills, and stimulate creativity through a combination of different approaches and methods. This learning format fosters a deeper understanding of the interrelationships between different fields of knowledge, enabling future military professionals to adapt to changing environmental conditions, collaborate in interdisciplinary teams, and develop innovative solutions at the intersection of industries.

At the same time in Ukraine, the introduction of STEAM education in military training is gaining momentum, and it is already proving its effectiveness, as it fosters systematic thinking, the development of analytical skills, creativity, and innovation in solving military tactical and strategic tasks. The implementation of the STEM approach in the educational process of training military specialists requires solving certain rather challenging tasks. Thus, for the effective development of STEM education, the main tasks are as follows:

– training and professional development of academic staff;
– development of scientific and methodological support and introduction of modern teaching aids;
– expanding the network of regional STEM centers and laboratories;
– conducting scientific and applied research (STEM education), etc.

Not all of the above tasks can be fully fulfilled in the current conditions of a full-scale invasion, but, in our opinion, this is not a reason to abandon the STEAM approach - we should try to implement its capabilities through the forms available at this stage (Matsai & Gubska, 2023, p. 45).

The primary challenges in implementing interdisciplinary learning stem from the organizational, methodological, and personnel aspects of the educational process. Firstly, there are often difficulties in coordination between different faculties and teachers due to varying curricula, standards, and teaching approaches. Secondly, the insufficient level of training of teachers, who must possess knowledge in several fields simultaneously, makes it difficult to create high-quality interdisciplinary content. Thirdly, curricula sometimes have rigid boundaries that do not allow for sufficient flexibility to integrate different disciplines. Additionally, there are challenges in assessing learning outcomes, as various competencies must be considered. Finally, the lack of adequate facilities and financial resources may hinder the introduction of new technologies and methodologies that support interdisciplinary learning in military education institutions.

The need to update curricula and faculty qualifications is driven by rapid changes in professional requirements and technological advancements, which necessitate those educational institutions respond flexibly to the challenges of the times. The curricula should integrate new interdisciplinary approaches, combining linguistic and professional competencies to ensure comprehensive training of modern military professionals. At the same time, teachers need regular professional development to master the latest methods, digital tools, and interdisciplinary practices, enabling them to teach effectively and adapt the material to the needs of military education students. Such a systematic approach will ensure the quality of education, the relevance of knowledge, and the competitiveness of students in the modern, globalized, and digital world (Shvets, 2025, pp. 280-281).

We would like to emphasize that in Ukraine, the development of STEAM education presents significant opportunities for training qualified military professionals capable of generating innovative ideas and solving complex problems of the modern world. It also contributes to the country's economic growth and international competitiveness. Therefore, we should not abandon the implementation of this approach in Ukraine. The introduction of STEAM education at the international level has demonstrated numerous positive results that can serve as an example for other countries, including Ukraine. Countries with the successful implementation of STEAM education, such as Canada, the United States, Singapore, and Finland, have clear national strategies and programs that provide funding, resources, and political support to promote the systematic development and integration of STEAM education into curricula (Bocharova, 2024, p. 33).

For example, Canada is providing advisory assistance under the Promoting Reform Objectives through Technical Expertise and Capacity Transfer (PORTEST) project to audit the military education system in Ukraine and to conduct a comprehensive functional review of the defence management system in the Ministry of Defence and the Armed Forces of Ukraine. To this end, a Memorandum of Intent on cooperation was signed with the Canadian company Alinea International (Zelnytskyi, 2022, p. 77).

Project "Technical Expertise and Capacity Transfer for Reform Support" – Structural Unit on Euro-Atlantic Integration of Ukraine (PROTECT).

1. Proposals have been developed for the Model Regulation on the responsible structural unit for Euro-Atlantic integration of Ukraine.
2. Proposals have been prepared for the Methodological Recommendations on the annual identification of the needs of ministries, other central executive authorities, and state bodies whose jurisdiction covers the entire territory of Ukraine, in "specialists on Euro-Atlantic integration of Ukraine and their professional training."
3. A general short-term advanced training program has been developed: "Development, Monitoring, and Evaluation of the Results of the Implementation of the Annual National Programs under the auspices of the Ukraine–NATO Commission."
4. A general professional (certificate) advanced training program has been developed: "Euro-Atlantic Integration of Ukraine."
5. A special short-term advanced training program has been developed: "Training of Trainers on the Principles and Approaches to the Development, Monitoring, and Evaluation of the Results of the Implementation of the Annual National Programs using the Result-Based Management (RBM) methodology."
6. Training has been organized for representatives of state authorities and higher education institutions under the advanced training program: "Development, Monitoring, and Evaluation of the Results of the Implementation of the Annual National Programs under the auspices of the Ukraine–NATO Commission."

Figure 4. Content of the project "Technical Expertise and Capacity Transfer to Support Reforms" (Partners' Forum, 2021, p. 7).

It is worth noting that as part of this study, a survey was conducted among third-year students of the Hetman Petro Sahaidachnyi National Army Academy. The study involved 112 respondents, which enabled the identification of their attitudes towards the implementation of the STEAM approach, assessment of the importance of interdisciplinary training, and the role of a foreign language teacher in the development of professional and communicative competences.

Analyzing the survey results, several important trends have been identified regarding the perception and importance of the STEAM approach in training military professionals. Thus, 76% of respondents noted that integrating natural and mathematical subjects with humanities (including a foreign language) contributes to better learning and the development of interdisciplinary competencies. At the same time, 64% of respondents stated that the use of STEAM elements by foreign language teachers (project tasks, working with digital tools, and situation modeling) directly increases motivation to learn. At the same time, 42% of cadets reported difficulties in using a foreign language when studying technical or tactical topics, which indicates the need for more practice-oriented classes. A significant proportion of respondents (58%) stressed the importance of developing intercultural communication competence, seeing it as a prerequisite for effective interaction with NATO partners. Additionally, 81% of respondents positively assessed the role of a foreign language teacher as a coordinator of interdisciplinary learning, facilitating the integration of knowledge from different fields in practical tasks. Only 12% of respondents expressed skepticism about the feasibility of implementing STEAM in military education, arguing that the curriculum is overloaded.

Thus, the results of the survey of higher military education students of the Hetman Petro Sahaidachnyi National Army Academy confirm the high relevance of the STEAM approach for the training of military specialists and emphasize the key role of the foreign language teacher in ensuring interdisciplinary integration and developing readiness for professional activity in the context of international cooperation.

Conclusions

The study demonstrates that adopting the STEAM approach in the training of military specialists, particularly within the Ukrainian–Canadian educational dialogue, redefines the role of a language teacher. The teacher becomes not merely an instructor but a multidisciplinary mentor who facilitates the integration of linguistic, technical, and professional components of learning. This transformation enables a shift from isolated subject teaching to a system in which language education contributes directly to the intellectual, communicative, and creative development of future military leaders.

The effective incorporation of STEAM principles into military education ensures that language learning is no longer a separate academic requirement but a functional instrument for professional growth. A competent foreign language teacher supports this integration by designing authentic communication tasks that link them to real operational contexts and developing the analytical and intercultural skills necessary for participation in multinational missions. Through this approach, students learn to apply language as a means of cognition, coordination, and leadership in complex professional environments.

Sustainable progress in this field depends on the teacher's continuous professional development. Mastery of language pedagogy must be complemented by familiarity with military-specific terminology, engineering concepts, and digital technologies. Participation in research projects, methodological workshops, and interdisciplinary collaborations enhances the teacher's ability to tailor educational materials to contemporary military needs. This ongoing refinement of expertise ensures that the integration of language and professional education remains both pedagogically sound and practically relevant.

Canada's long-standing experience in implementing STEAM education confirms that an integrated and innovative model of learning is a decisive factor in building professional adaptability and technological literacy among military personnel. Ukraine, facing the challenges of modern warfare and global transformations, can effectively adapt these best practices by investing in teacher training, infrastructure, and strategic cooperation between education and defense institutions.

Ultimately, the STEAM-based paradigm equips future officers with not only linguistic and technical competence but also with creativity, analytical reasoning, and flexibility, qualities that define a modern professional capable of making informed decisions and engaging in effective international collaboration. The foreign language teacher, therefore, stands at the intersection of knowledge domains, acting as a key agent of transformation within the evolving system of military education.

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4.2. Formation of Environmental Competence of Senior Grade Students in the Process of STEM-Learning Using Project Technologies

Alina Truten, Svitlana Tolochko

Abstract. *The article explores the theoretical and practical foundations for developing environmental competence among senior-grade students through STEM-based education and project-based learning (PBL). The concepts of environmental competence, STEM education, and project-based learning are examined, and their interrelations within the modern educational paradigm are clarified. The study demonstrates that integrating interdisciplinary approaches, inquiry-oriented methods, and digital tools in STEM education enhances students' ability to apply environmental knowledge in real-life situations and cultivates a responsible attitude toward nature. Project-based learning is identified as an effective pedagogical strategy for fostering environmental awareness, critical thinking, teamwork, and research skills, which are essential for addressing contemporary ecological challenges. A model for implementing environmentally oriented STEM projects in secondary schools is proposed, emphasizing practical orientation, research activity, and collaboration between students, teachers, and local communities. The study highlights the Ukrainian experience in introducing ecological STEM initiatives and correlates it with international practices, demonstrating that this approach effectively combines theoretical knowledge with practical action, thereby contributing to the achievement of the Sustainable Development Goals.*

Keywords: *environmental competence, senior-grade students, STEM education, project technologies, environmental education.*

Introduction

The modern education system is undergoing a profound transformation, driven by both internal social needs and global challenges. One of the most pressing tasks today is addressing the ecological crisis, which is manifested through climate change,

DOI: 10.31110/STEM-CaUk-4.2

environmental degradation, biodiversity loss, and a depletion of natural resources. In these conditions, the formation of environmental awareness and competence in the younger generation, capable not only of recognizing environmental problems but also of actively participating in their solution, acquires special importance. The education system is designed not only to inform, but also to cultivate a responsible attitude towards the environment, forming students' environmentally appropriate motivation, critical thinking, and skills for practical activities in the environmental sphere. In conditions of war, the problem of environmental protection becomes even more acute: large-scale pollution of air, water, and soil, destruction of ecosystems, accumulation of toxic substances, and an increase in technogenic and radiation risks pose new challenges to education. The formation of students' environmental competence is becoming not only an educational, but also a strategic national task. Accordingly, a modern school must provide conditions for the development of students' environmental awareness, understanding of the cause-and-effect relationships between human activity and the state of the environment, as well as the ability to act environmentally responsibly in both everyday life and emergency situations.

The urgency of finding new approaches to the educational process highlights the need to integrate a scientific base, interdisciplinarity, practical orientation, and active student participation. One of the promising areas for updating the content of high school education is the STEM approach (Science, Technology, Engineering, and Mathematics), which combines the natural sciences, technology, engineering, and mathematics to prepare students to solve real-life problems, develop innovative solutions, and foster critical thinking.

The STEM approach, combined with project-based technologies, contributes to the development of key competencies defined by the State Standard of General Secondary Education: the ability to learn throughout life, initiative, innovation, environmental literacy, and technological literacy. In the field of environmental education, STEM is focused not only on transforming knowledge about the environment but also on engaging students in active research, analysis, modeling, forecasting, and the development of practical, solutions-oriented approaches.

Project-based learning, as one of the effective forms of implementing the STEM approach, orients students to achieve significant results – projects that have practical or social value. In the process of creating environmental STEM projects, senior-grade students not only acquire interdisciplinary knowledge and skills but also develop critical thinking, research competence, and the ability to work in a team. The combination of natural knowledge with technical thinking and awareness of environmental challenges forms students' holistic vision of human interaction with the environment. Environmental projects enable students not only to explore current issues but also to recognize themselves as agents of change, capable of influencing the state of the environment through targeted actions.

Scientific analysis suggests that project technologies in STEM education can enhance the development of environmental competence; however, the issues of their methodological support and optimization remain understudied. This is especially true for high school, where the formation of students' conscious environmental position and active civic position takes place. The relevance of developing environmental competence in senior-grade students through STEM education has led to the need for an in-depth analysis of this issue, which informed the topic of this scientific research.

The purpose of this study is to analyze the theoretical and practical aspects of developing environmental competence in senior-grade students through STEM education, utilizing project-based technologies.

To achieve this goal, the following tasks are *planned*:

1) to analyze the basic concepts: «ecological competence», «STEM education, «project technologies»;

2) to reveal the features of STEM education as an innovative direction for the formation of senior-grade students ' environmental competence;

3) to analyze modern approaches to the use of project technologies in the process of STEM education for the formation of environmental competence;

4) to develop a model for the implementation of STEM projects of an ecological orientation with the involvement of project technologies in secondary education institutions.

To achieve the set goal and defined tasks, the following methods were used: theoretical: theoretical analysis and generalization of literary sources – in order to analyze the problem of forming environmental competence of senior-grade students in the process of STEM-learning using project technologies; comparison, classification, generalization to clarify the content of the main concepts of the study; deductive, inductive methods – to determine the features of STEM education as an innovative direction of forming environmental competence of senior-grade students ; systemic method, formalization – to develop a model for implementing STEM-projects of an environmental direction with the involvement of project technologies in secondary education institutions; idealization and pedagogical modeling – in order to design a system of environmental competence of senior-grade students in the process of STEM-learning using project technologies; empirical: pedagogical observation, generalization of pedagogical experience – in order to generalize the state of use of project technologies in the process of STEM-learning for the formation of environmental competence.

Research Results

The formation of senior-grade students ’ environmental competence is one of the key goals of modern education focused on sustainable development. In the context of global environmental challenges, including climate change and degradation of natural resources, as well as the need to implement the principles of responsible consumption, school education should provide students with not only knowledge but also practical skills, motivation, and values for environmentally responsible behavior.

One of the most promising approaches to achieving this goal is a combination of STEM education and project technologies.

STEM education – an interdisciplinary educational approach that combines knowledge from natural sciences, technology, engineering, and mathematics – opens up wide opportunities for understanding and solving environmental problems in practice. In turn, project-based technologies enable you to implement tasks that closely resemble real-life situations, which foster students' critical thinking skills, cooperation, and research activities, while also increasing their environmental awareness.

According to O. Matvienko and M. Fatich The acronym STEM is interpreted as: «science – the study of the natural world; technology – the definition of STEM technology includes any product created by people to meet needs, that is, a product that children create to solve a problem; engineering – the design process; mathematics – the language of numbers, shapes and quantities» (Matvienko et al., 2019, p. 123). According to the authors, STEM is not just a grouping of subject areas, but a movement to develop deep mathematical and scientific foundations that must be competitive in the 21st century.

In contemporary educational discourse, ecological STEM education is regarded as an effective tool for fostering students' competencies in sustainable development, critical thinking, and innovative activity (UNESCO, 2020). International experience demonstrates that integrating ecological components into STEM processes is achieved through various models and approaches that ensure interdisciplinarity, practical orientation, and project-based learning.

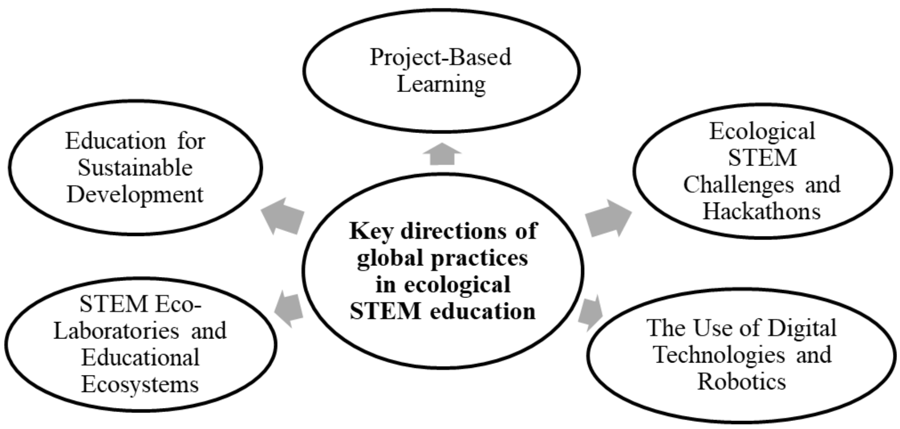

Figure 1. Key directions of global practices in ecological STEM education
Source: developed by the authors based on the reviewed literature

Project-Based Learning. In the United States and Canada, project-based learning is recognized as one of the leading approaches to organizing the educational process, particularly within ecological STEM education. Students are engaged in addressing local environmental issues, ranging from monitoring water quality in nearby bodies of water to designing models of «green» buildings that comply with the principles of energy efficiency and sustainable development (Krajcik & Blumenfeld, 2006). Such practices foster students' research skills, enhance critical thinking, and integrate knowledge from the natural sciences, technology, and engineering. In Ukraine, this approach is gradually gaining ground: in general, secondary education institutions are implementing ecologically oriented STEM projects that focus on environmental monitoring, energy efficiency, and waste management (Hurevych et al., 2021).

Ecological STEM Challenges and Hackathons. In many European countries and in Australia, school-based challenges and hackathons focused on addressing pressing environmental issues have gained significant popularity. Students work collaboratively on tasks related to developing innovative technologies aimed at reducing CO_2 emissions, improving waste sorting and recycling, or creating renewable energy sources (European Schoolnet, 2022). Such educational practices not only cultivate creativity and engineering thinking but also encourage students' social responsibility. In Ukraine, this approach has been reflected in a number of competitions, including *«MAN-Junior»* and the *«All-Ukrainian Contest of Ecological Projects»*, which motivate students to design their own eco-technologies and solutions in the field of environmental protection (Antonchenko & Pavlenko, 2024).

The Use of Digital Technologies and Robotics. Innovative digital tools are increasingly being integrated into the process of ecological STEM education. For instance, in Finland and Japan, geographic information systems (GIS), digital sensors, and robotics are actively applied to analyze environmental conditions, enabling students to obtain real-time data on climate change, air quality, or water conditions (Nishimura, 2019). In Ukrainian schools, the practice of using digital sensors, mobile applications, and Arduino microcontrollers to study natural processes is also expanding, bringing the educational process closer to European

STEM education standards (osvita.ua, 2024). This contributes to the development of students' ability to work with large datasets and implement practical engineering solutions.

STEM Eco-Laboratories and Educational Ecosystems. Singapore serves as an example of establishing innovative STEM eco-laboratories, where students work on real environmental challenges, particularly in the areas of vertical farming and the development of sustainable agro-technologies. In Germany, Green STEM Labs, organized under the auspices of the Fraunhofer Society, engage students in research activities in bioenergy and renewable technologies (Fraunhofer Society, 2021). In Ukraine, researchers propose the creation of holistic STEM ecosystems that integrate educational institutions, research institutes, and local communities, aiming to foster ecological competence and develop innovative thinking (Hurevych et al., 2021).

Education for Sustainable Development. According to UNESCO's recommendations, STEM education is regarded as one of the key instruments for implementing the concept of «education for sustainable development», as it combines scientific knowledge with practical actions aligned with the Sustainable Development Goals (UNESCO, 2020). In Ukraine, this idea is being implemented within the framework of the New Ukrainian School concept, which identifies ecological competence as one of the cross-cutting key competencies. At the same time, the STEM approach in the educational process is viewed as the foundation for fostering innovative thinking and students' ability to critically analyze contemporary environmental challenges (MON Ukrainy, 2020).

Project-based learning has proven effective in developing students' practical, interdisciplinary, and social competencies across various countries. In particular, in Ontario (Canada), the implementation of project-based learning in science and technology courses contributed to a 15–20% increase in students' average grades and improved their critical thinking and teamwork skills (Thomas, 2000). Importantly, this approach promoted not only academic progress but also the ability to make decisions in real-life situations. In the United States, research by the Buck Institute for Education indicates that students engaged in project-based learning demonstrated better outcomes in acquiring interdisciplinary STEM knowledge, particularly in the field of ecology (Bell, 2010). Special emphasis was placed on developing practical skills for environmental research, which enhanced students' engagement and active participation.

In Sweden, the implementation of project-based learning in the course *«Ecology and Sustainable Resource Management»* enabled students to develop real eco-projects for local communities, which not only increased their motivation but also contributed to the development of research skills, activity planning, and teamwork abilities (Larsson & Holmberg, 2013). Similar experiences confirm the versatility of the method, which effectively combines educational objectives with socially beneficial activities. Comparable results are also observed internationally during hackathons and STEM challenges, where project-based activities stimulate the practical application of knowledge, foster leadership and communication competencies, and promote entrepreneurial thinking (Capraro et al., 2013).

In Ukrainian general secondary education institutions, elements of project-based learning are also being actively implemented. Within the framework of the New Ukrainian School and the activities of the Junior Academy of Sciences of Ukraine, students engage in interdisciplinary ecological STEM projects, which include monitoring the condition of water bodies, air quality assessment, the development of energy-saving models, and «green» architectural solutions (Hurevych et al., 2021). Educational competitions and initiatives, such as the *All-Ukrainian Contest of Ecological Projects*, are also widespread, where students present their own solutions for local communities, combining learning with a practical contribution to the development of a sustainable environment (Antonchenko & Pavlenko, 2024).

Thus, project-based learning in ecological and STEM education performs a dual function: on the one hand, it ensures the integration of theoretical knowledge with practical skills, and on the other hand, it prepares students to address current global and national challenges, including environmental issues and sustainable development objectives.

The effective functioning of a STEM educational environment is ensured by a set of key elements that contribute to the development of the necessary competencies in students (Polihun et al., 2019). Let us consider it in more detail.

Table 1. Important components of a STEM educational environment

No	*Components of a STEM educational environment*	*Characteristic*
1.	Integrated curricula and elective courses	Based on a competency-based approach that involves the formation of practical skills and abilities. The development of creative educational content requires the cooperation of teachers, specialists in industry sciences, and representatives from industry and business, ensuring the relevance and practical orientation of training. This approach enables students to effectively apply their knowledge in real-world conditions and prepares them for the demands of the modern labor market.
2.	Adherence to interdisciplinary principles of learning	This approach enables students to tackle problems that transcend the boundaries of a single academic discipline, fostering their development of systemic thinking. Particular attention is paid to real-life and technological challenges that students face in conditions of incomplete or limited knowledge, which encourages them to find non-standard solutions, use available resources, experiment, and independently obtain information.
3.	Practical-oriented learning	It plays a crucial role in developing students' applied skills, enabling them to apply theoretical knowledge in real-world or simulated situations. This approach is implemented both within STEM disciplines and in extracurricular space – through projects, competitions, workshops, and club activities. This contributes to increased motivation, the development of creativity, and enhanced team interaction.

4.	Student project, team, and group activities	Among the leading forms of organizing the educational process, it is worth noting projects, integrated lessons, quests, case methods, excursions, theme days, competitions, scientific exhibitions, and engineering festivals. These forms are designed to develop critical thinking, teamwork, creativity, and the ability to independently solve practical problems. They contribute not only to the acquisition of knowledge but also to the development of key competencies necessary for successful self-realization in a modern digital society.
5.	Creating functional activity zones in the classroom	Zones for research, creative and communicative activities, as well as presentation platforms. Such an organization promotes the development of key competencies, fosters effective interaction, and encourages active student involvement in the educational process.
6.	Using modern teaching tools	Robotic sets (LEGO, LEGO Mindstorms, Cubelets, LittleBits, MakeBlock) that promote the development of skills in mechanics, electronics, programming, and engineering design. Additionally, digital measuring systems, microprocessor devices, programming tools, and network platforms are utilized to ensure that STEM education is inclusive and accessible to all students.
7.	Establishing cooperation between general secondary education institutions and external partners	Higher education institutions, scientific institutions, laboratories, museums, natural history centers, enterprises, and public organizations, among others. Such interaction contributes to the enrichment of the educational process, ensures the integration of theory with practice, and expands students’ opportunities in gaining applied experience and involvement in scientific and technical projects. Thanks to joint initiatives, an open, innovative, and future-oriented educational environment is created, in which students are not only consumers of

		knowledge but also active participants in its creation.
8.	Active involvement of the parent community in STEM educational initiatives	It is an important condition for the effective functioning of the STEM environment. Parents not only support educational activities but also act as partners in implementing project activities, contributing to the organization of excursions, competitions, and meetings with specialists in the fields of science and technology. This fosters intergenerational cooperation and promotes a practical approach to learning.
9.	Systematic monitoring of learning outcomes	It involves not only assessing students' achievements but also analyzing the dynamics of their development, engagement in the learning process, and the effectiveness of the pedagogical strategies applied. Monitoring encompasses both quantitative and qualitative indicators, enabling you to identify strengths and areas for improvement, and adjust the educational trajectory accordingly to meet the needs of students and achieve program goals. This approach ensures flexibility in educational interaction and increases the effectiveness of STEM education.

Source: created by the authors

The features of STEM education as an innovative direction for developing senior-grade students ' environmental competence lie in its interdisciplinary approach and practical orientation. The integration of knowledge in science, technology, engineering, and mathematics provides a holistic understanding of environmental processes and phenomena, allowing students to see the connections between theory and real environmental challenges. The orientation towards project activities contributes to the involvement of schoolchildren in practice-oriented environmental initiatives, fosters a responsible attitude towards nature, develops research skills, and enhances the ability to solve both local and global problems related to sustainable development.

A crucial component is the development of critical and systemic thinking, which is necessary for analyzing complex environmental situations, assessing risks, and finding effective solutions through an interdisciplinary approach. The use of digital technologies, particularly data visualization, digital laboratories, and process modeling, enhances the research component and enables effective monitoring of the environment's state. STEM education also involves team interaction, which develops communication skills, the ability to work in a group, and the capacity to make collective decisions. Participation in socially significant eco-projects contributes to the formation of environmental awareness and a sense of responsibility to the community.

At the same time, STEM education motivates students to pursue scientific and professional self-realization in environmentally oriented areas, such as environmental protection, eco-engineering, and biotechnology. Ultimately, it is the approach that prepares students for the challenges of sustainable development, providing them with knowledge, skills, and tools to achieve the relevant Sustainable Development Goals - in particular in the areas of water resources protection, biodiversity conservation, combating climate change, and ensuring energy efficiency (Vasilashko et al., 2020).

Students' ecological competence, according to the State Standard of Basic Secondary Education, includes the ability to understand the ecological foundations of nature use, the need to protect nature, comply with the requirements of behavior in nature, use natural resources economically, understand the significance of the context and interdependence of economic activity and the need to preserve nature, which will contribute to ensuring the sustainable development of society (Tolochko et al., 2024, p. 51).

Ecological competence has a complex structure, which is formed through the integration of a number of key components:

– cognitive (awareness of the state of the environment, factors of its degradation, and ways of preservation);

– value (conscious attitude to nature and understanding of its value);

– activity (ability to environmentally appropriate behavior in everyday life);

– emotional and motivational (readiness to act for the benefit of the environment, motivation to participate in environmental protection activities).

One of the options for productive learning is project-based learning, the purpose of which is not to master a large amount of knowledge or complete educational programs, but to actually use, develop, and enrich students' own experiences and their understanding of the world. The essence of project-based learning is that, based on their interests, children, together with the teacher, design a solution to a practical task. The material of various educational subjects is grouped around project complexes. Educational design is primarily focused on students' independent activity, whether individual, group, or collective, which they perform over a specified period (Zalozna, 2022).

The main types of educational projects that are implemented in the educational process, taking into account the didactic goal, the method of organizing student activity, and the specifics of the final product, are shown in Figure 2.

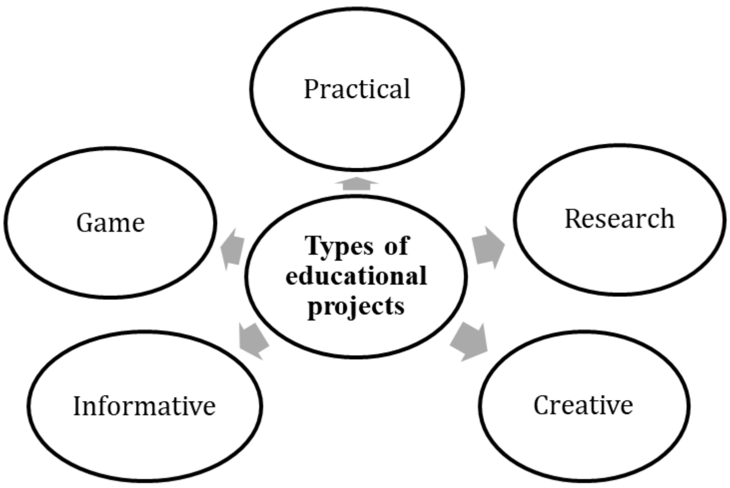

Figure 2. Main types of educational projects
Source: created by the authors

Creative projects involve the implementation of ideas that lack a rigidly structured framework. The organization of joint activities among participants is based on a preliminary agreement regarding the expected result and the methods of its representation. Such projects focus on developing creative thinking, aesthetic taste, and the ability to express oneself. Examples of final products can be a handwritten journal, a collective collage, a video film, a thematic evening, or a creative holiday.

Game projects are characterized by the inclusion of elements of role-playing interaction. Participants assume roles determined by the project's content and purpose, allowing them to model interpersonal, social, or professional relationships. The role-playing component can be based on both fictional characters (such as literary or fairy-tale figures) and real historical or modern figures. This form helps develop communication skills, empathy, and a critical understanding of social information.

Information projects aim to obtain, process, and present information on a certain phenomenon, event, or problem. They involve independent search, selection, systematization, analysis, and generalization of factual material, with subsequent presentation of the results obtained in the form of a review, analytical report, presentation, or other similar formats. The primary emphasis is on developing students' information and analytical competence.

Practically oriented projects aim to create a real, socially significant product. Their result is clearly defined at the initial stage and is directly related to the needs of the student body or local community. These can be various documents, programs, recommendations, directories, models, and environmental initiatives (for example, a school garden project or landscaping of the territory). The implementation of such projects requires detailed planning, distribution of functions, a clear scenario of activities, regular coordination of work, and presentation of the achieved results.

Research projects are the most academically oriented. They require a scientifically sound structure, including the formulation of a clear goal and hypothesis, the selection of the study's object and subject, as well as the application of methods for data collection and analysis. Research projects involve a deep immersion in the problem, including conducting observations, experiments, surveys, and other relevant activities. Special attention is paid to the processing and interpretation of results, which form scientific thinking skills and academic integrity in students.

In the process of project-based learning activities, students develop general educational skills and abilities that cover several key areas:

– reflective skills, which include the ability to consciously analyze the task, formulate questions such as: «Why do I need to learn this to solve the problem? »;

– search and research skills, which include the ability to independently generate ideas, search for and process missing information, offer alternative solutions to the problem, put forward hypotheses, and establish cause-and-effect relationships;

– teamwork skills, including the ability to plan collective activities, cooperate to achieve a common goal, communicate effectively, help each other, and analyze and correct the actions of team members;

– managerial competencies, which include the ability to design an activity or product, rationally plan time and resources, make decisions taking into account the forecast of possible consequences, and also conduct self-analysis of the process and intermediate results of work;

– communication skills, which include initiating learning interaction, conducting constructive discussions, arguing one's own position, the ability to find compromises, mastering oral questioning and interviewing techniques;

– presentation skills, including the ability to confidently speak in front of an audience, possess elements of stage expressiveness, use visual materials to enhance the report, and answer unexpected questions (Zapopadna).

An educational project in teachers' activities is considered an integrated didactic tool that combines educational and instructional functions, focusing on the development of learners' competencies. Its implementation involves the sequential processing of the following stages:

– analysis of the problem situation and definition of the key problem; setting tasks and forming goals;

– planning one’s own activities;

– searching, selecting, and organizing the necessary information;

– choosing and applying the technology appropriate to the problem and determining the final product;

– conducting research activities (analysis, synthesis, formulating hypotheses, detailing, generalization);

– using the acquired knowledge and skills in various, including non-standard, situations;

– conducting self-analysis and reflection on the effectiveness of the actions performed;

– presenting the activity and its results, forming a positive image of one’s own work (Vovk et al., 2021).

In the process of implementing project activities, the teacher plays several key roles (Fig. 3).

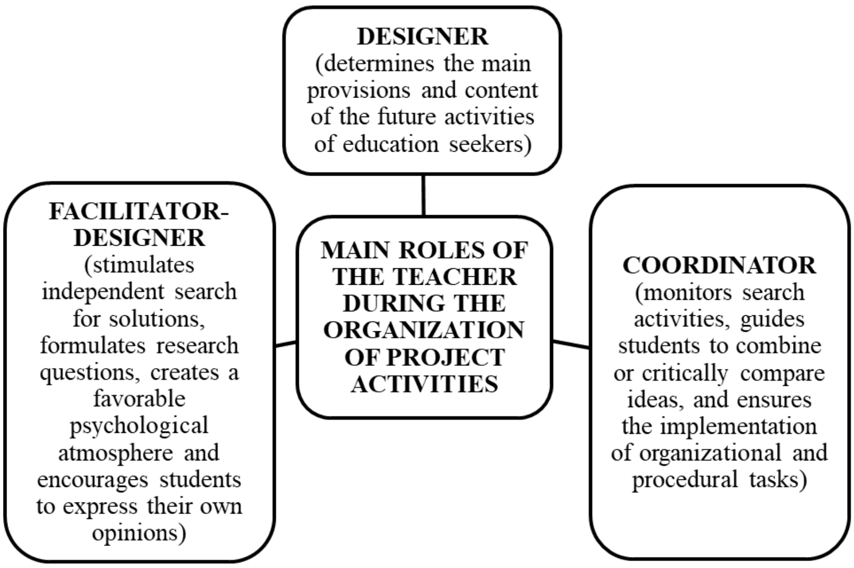

Figure 3. The main roles of the teacher during the organization of project activities
Source: cited from O. Ilyina (2021).

The school's educational team can effectively implement STEM projects using the following forms of activity organization:

– problem-based learning, which stimulates students to actively think and search for solutions;

– research lessons, during which the teacher first formulates the problem, and students look for ways to solve it, based on the questions posed. Subsequently, students independently identify problems (with the support of the teacher), form hypotheses, independently select solutions, and summarize the results of the work together with the teacher;

– short-term observations-research with a description of the results under the guidance of the teacher;

– familiarizing students with theoretical concepts of research activities, in particular with research methods, working with primary sources, analysis, and formation of conclusions;

– conducting collective research, organized according to a predetermined plan and taking into account all key stages of scientific research, based on current topics (Vasilashko, 2020, p. 9).

Involving senior-grade students in environmental project activities contributes not only to deepening their knowledge and practical skills but also to the formation of a responsible attitude towards the environment and the development of creative thinking. Participation in such projects offers students the opportunity to actively contribute to the environment and make informed decisions about the sustainable future of the planet (Tolochko, 2024).

The structure of an environmental project includes a number of interrelated components, including: identifying a current need, conducting analytical research (analysis of existing analogues or solutions), formulating requirements for the design object, generating initial ideas, their critical analysis and a reasoned choice of the optimal option, planning actions, manufacturing or implementing the development, as well as evaluating the result and reflecting.

The implementation of environmental projects within the framework of STEM education is a crucial component in forming students' comprehensive knowledge, skills, and values that promote sustainable development and environmental preservation. This process involves the phased planning and implementation of activities that allow for systematic solutions to environmental problems, integrating interdisciplinary approaches from science, technology, engineering, and mathematics. The main stages of implementing such projects, which ensure the consistent and effective achievement of the set goals, are presented below (Fig. 4).

1. **Preparatory stage,** covering content and technological preparation;
2. **The planning stage,** which includes formulating the problem and determining a strategy for solving it;
3. **Research stage,** associated with the analysis of the problem situation and the choice of the optimal way to overcome it;
4. **Activity stage,** which involves the direct implementation of planned actions;
5. **Presentation stage,** where the results are presented;
6. **A reflective stage,** which includes analyzing the effectiveness of the activities performed, evaluating achievements, and identifying areas for further improvement.

Figure 4. Stages of implementing environmental projects within STEM education
Source: created by the authors

The use of such stages ensures systematic, interdisciplinary, and practice-oriented learning, aligning with modern educational approaches and contributing to an increase in students' environmental awareness.

In this context, project activities within STEM education serve not only as a didactic tool but also as an effective means of developing students’ environmental competence. Its integrative nature provides a combination of knowledge from natural sciences, technologies, engineering, and mathematics to solve current environmental problems. Thanks to this, students have the opportunity not only to deepen their subject knowledge but also to gain practical experience in applying it in real or nearly real-world conditions.

Project activities in the STEM direction stimulate the development of research skills, critical and systemic thinking, the ability to analyze environmental situations, and find ways to solve them based on scientific approaches. At the same time, such activities contribute to the formation of value orientations, a responsible attitude towards nature and the environment. Students recognize the importance of their own participation in environmental conservation, which enhances their personal interest in the educational process and the project's results. Thus, the STEM approach in project activities creates conditions for the holistic development of environmental competence as a key component of a sustainable educational process.

At the same time, implementing the STEM approach using project technologies presents several challenges. In particular, it requires increasing the level of teacher training, readiness for interdisciplinary teaching, the availability of educational and methodological support, and the appropriate material and technical base. In addition, it is essential to consider students' individual characteristics, motivation, and the level of foundational knowledge in the natural sciences field.

Digital tools, online platforms for collaboration, data visualization services, means of remote communication, and technologies for monitoring environmental indicators all open up new opportunities for organizing effective project activities within the STEM education framework. The use of resources such as Google Workspace, Zoom, Padlet, Canva, ThingLink, ArcGIS, EcoSchools, EcoMonitoring, and others allows you to integrate elements of digital content into educational tasks, ensure an interdisciplinary approach, activate students' cognitive activity, and stimulate them to independently research environmental problems and find ways to solve them.

Digital technologies facilitate the visualization of complex environmental processes and phenomena, which is especially important in high school, where students are capable of analytical thinking and critical assessment. They also provide mobility, access to relevant scientific information, and open up numerous opportunities for international cooperation, the exchange of experiences, and participation in global environmental initiatives. In combination with project technologies, digitalization contributes to the creation of a modern educational environment, where the development of environmental competence becomes systematic, practical, and sustainable, leading to learning outcomes. Thus, digital tools act not only as a technical means, but also as a pedagogical factor that enhances the effectiveness of forming environmental awareness and students' readiness for environmentally responsible behavior in the real-world conditions of the modern world.

The integration of project technologies into STEM education enables students to participate in solving current environmental problems, work in teams, analyze results, and present their own ideas. To systematically organize such activities, a model for implementing STEM projects with an environmental focus using project-based technologies in secondary education institutions has been developed (Fig. 5). This model defines the key principles, components, stages of implementation, and expected results of integrated educational activities.

The model for implementing STEM projects with an ecological orientation, involving project technologies, involves creating an effective educational environment that fosters the development of students' environmental competence through interdisciplinary interaction and research activities. Its goal is to form students' environmental competence through the implementation of practice-oriented STEM projects.

The implementation of the model is based on the principles of integrativity, practical orientation, research approach, team interaction, and active community participation. Students, teachers, STEM specialists, and local community representatives are involved in the implementation of the projects.

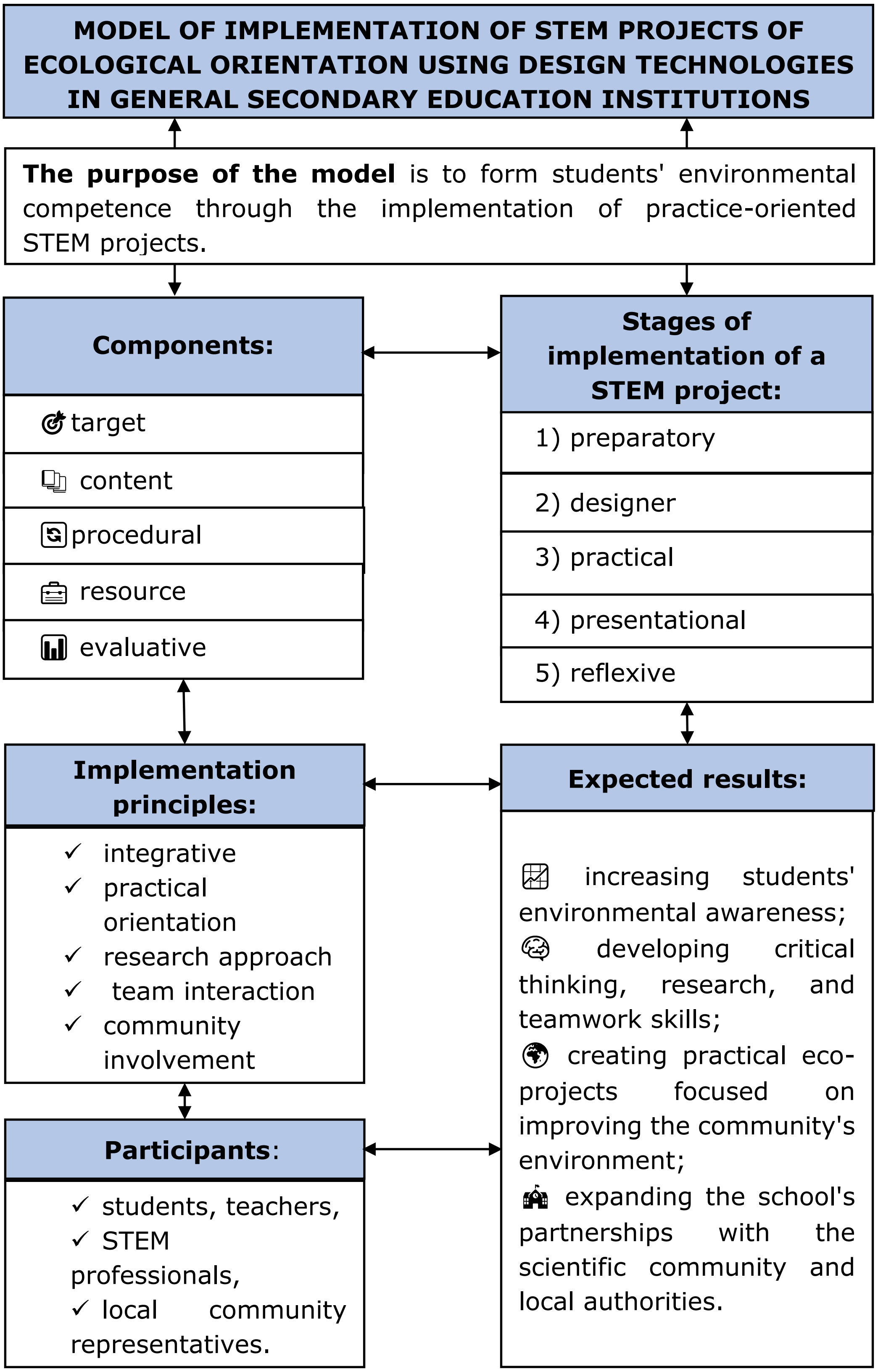

Figure 5. Model for implementing STEM projects of an ecological nature using project technologies in secondary education institutions
Source: created by the authors

Project activities are implemented in stages:

– at the preparatory stage, the problem is identified, teams are formed, and activities are planned;

– at the design stage, ideas, hypotheses are developed and methods are selected;

– the practical stage includes data collection, experiments, and product creation using digital tools;

– the presentation stage involves visualization of results and public defense;

– the reflective stage – assessing the effectiveness of the project and identifying opportunities for its scaling.

The expected results include an increase in students' environmental awareness, the development of critical thinking, research, and teamwork skills, the creation of practical eco-projects aimed at improving the community's environmental condition, and the expansion of the school's partnerships with the scientific community and local authorities.

Table 2 presents a selection of educational STEM projects of an ecological orientation for implementation in the educational process:

Table 2. Educational STEM projects with an ecological focus for implementation in the educational process

No	*Project topic*	*Project goal*	*STEM components*
1.	Clean Water – Healthy Community 	Investigate the quality of water in local sources and suggest ways to improve it.	**S (science):** analyze water samples (pH, hardness, contamination); **T (technology):** create a digital presentation of the results; **E (engineering):** design a filter or model of a purification system; **M (math):** calculate averages, build graphs.

2.	Green School: Energy Efficient 	Assess the level of energy consumption in the school and develop an energy-saving plan	**S:** study energy sources and their impact on the environment; **T:** use sensors or applications to collect data; **E:** create a model of an energy-efficient building; **M:** analyze energy consumption in kWh, economic calculation.
3.	Sorting is saving! 	To study the state of waste management in the community and popularize waste sorting.	**S:** classification of waste types, environmental impacts; **T:** creation of a mobile application/bot with instructions for sorting; **E:** development of containers for collecting recyclables; **M:** statistics of waste at school, reduction in volumes after the introduction of sorting.
4.	Monitoring the condition of the soil in our area 	Determine the fertility and level of soil pollution in various regions of the area.	**S:** study of acidity, presence of nitrates; **T:** use of GPS, Google Maps to plot data on the map; **E:** proposals for reclamation or greening of areas; **M:** analysis of changes by season, statistical processing of results.

5.	Pollinator protection: biodiversity in action 	Investigate the role of pollinators (bees, butterflies) and develop initiatives for their conservation.	**S:** biological importance of pollinators, food chains; **T:** creation of an information website or interactive map of distribution areas; **E:** development of «houses» for insects, planting of honey plants; **M:** recording the number of pollinators in different areas.

Source: created by the authors

Let's consider the stages of implementing the educational STEM project «Clean Water – Healthy Community» for senior-grade students. The project aims to raise the environmental awareness of senior-grade students by researching the quality of water in their region and developing practical recommendations for its improvement. Within the framework of this project, students apply an interdisciplinary approach, integrating knowledge from natural sciences, technology, engineering, and mathematics, which is the basis of STEM education. Such practical experience not only helps master theoretical material but also develops the skills of research work, critical thinking, and teamwork, while fostering environmental competence and a responsible attitude towards the environment.

The purpose of the project: to investigate the quality of water in local sources and suggest ways to improve it.

Table 3 shows the stages of implementation of the project «Clean Water – Healthy Community», which reflects an integrated approach to the formation of environmental competence of senior-grade students within the framework of interdisciplinary research.

Table 3. Stages of implementation of the STEM project «Clean Water – Healthy Community» for senior-grade students

No	*Project stages*	*Description of actions*
1.	Problem definition and research planning	– Discuss the importance of clean water for community health and environmental threats. – Formulate the problem of water pollution. – Define the goals and objectives of the project. – Plan to collect samples from multiple sources (wells, rivers, boreholes).
2.	Data collection and analysis (Science)	– Collection of water samples at designated points. – Chemical analysis: pH, hardness, contaminants (metals, bacteria, etc.). – Recording of results in a table. – Primary analysis and comparison with safe water standards.
3.	Data processing and visualization (Mathematics, Technology)	– Calculation of average values of water quality indicators. – Creation of graphs and charts of pollution levels. – Preparation of digital presentation of results (PowerPoint, Canva, Google Slides).
4.	Development of a technical solution (Engineering)	– Proposal of options for filtration or water purification. – Creation of a filter layout or a model of a purification system (activated carbon, sand, gravel). – Modeling of the system operation and demonstration of efficiency.
5.	Project presentation and recommendations	– Presentation of results and developed models. – Discussion of recommendations for improving water quality. – Proposals for information campaigns to raise environmental awareness in the community.

6.	Reflection and evaluation	– Analysis of the results obtained and discussion of difficulties. – Determination of the formed competencies (ecological, mathematical, technological, engineering).

Source: created by the authors

Each stage of the project encompasses the key components of STEM education, including scientific analysis, technological data processing, engineering modeling, and mathematical information processing. The proposed structure fosters the development of practical skills, critical thinking, and a responsible attitude towards the environment, which are essential components in preparing modern youth to address current environmental challenges.

Thus, the mentioned STEM projects demonstrate the wide possibilities of integrating environmental topics into the high school educational process, ensuring an interdisciplinary approach and active student involvement in research activities. They contribute to the formation of key competencies, in particular, environmental awareness, critical thinking, data analysis and processing skills, as well as the ability to work with modern digital technologies. Thanks to the implementation of practically oriented projects, senior-grade students acquire not only theoretical knowledge but also important skills in design, modeling, and making responsible decisions in the field of environmental protection. Such an approach fosters environmentally responsible behavior, stimulates innovative thinking, and prepares students to contribute to solving pressing environmental problems at both local and global levels.

Conclusions

Thus, project technologies, in combination with STEM education, not only foster a high level of environmental awareness among senior-grade students but also equip them with the ability to make responsible environmental choices and take action in real life.

The study analyzed the basic concepts: «ecological competence», «STEM education», and «project technologies». The essence and content of each of these concepts were determined, as well as their relationship in the context of modern education.

The features of STEM education as an innovative direction were revealed, which consist of an interdisciplinary combination of knowledge in science, technology, engineering, and mathematics, practical orientation of learning, application of project and digital technologies, development of critical thinking, team interaction, participation in socially significant eco-projects, and orientation towards achieving the Sustainable Development Goals.

Modern approaches to the use of project technologies in STEM education, which serve as an effective tool for developing environmental competence, are analyzed. The study demonstrates that project activities enable students not only to integrate knowledge from various fields, including natural sciences, technology, engineering, and mathematics, but also to apply it in practice to solve real-world environmental problems. Project technologies contribute to the development of environmental competence by immersing senior-grade students in research activities, during which they independently identify problems, formulate questions, search for information, develop solutions, and evaluate results. This approach stimulates active cognitive engagement, fosters team interaction skills, promotes a responsible attitude towards the environment, and develops critical, systemic, and innovative thinking. An important component is also the development of practical skills, particularly in working with digital resources, conducting experiments, and creating environmentally oriented products or models.

A model for implementing STEM projects of an environmental focus with the involvement of project technologies in secondary education institutions has been developed, which takes into account the peculiarities of the educational process and is aimed at the consistent formation of students' environmental competence through the integration of interdisciplinary knowledge, which provides a systematic approach to solving modern environmental problems. The proposed model has significant implications and can be effectively integrated into the educational process to enhance the quality of environmental education.

Prospects for further research aim to enhance the methodological support for implementing the STEM approach in environmental education and to develop digital educational resources that support environmentally oriented STEM projects.

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EPILOGUE

Olena Semenikhina

1. Summary and Integration

As editors of this collective monograph, we close with a synthesis of ideas that emerged across its chapters, a conversation between research traditions, educational systems, and lived experiences. The comparative study of Canada and Ukraine has revealed more than national differences; it has uncovered the deep structural logic of STEM and STEAM education as a transformative cultural phenomenon that reshapes how societies learn, create, and innovate.

Throughout the book, a clear pattern emerges: STEM education serves simultaneously as a knowledge system, a policy tool, and a humanistic project. It connects global challenges, from climate change to digital transformation, with local solutions that rely on critical thinking, creativity, and collaboration. Chapter 1 (V. Shamonia & O. Semenikhina) provided the bibliometric and conceptual foundation for understanding this duality. By analyzing over twenty thousand records in Web of Science, the authors demonstrated that both Canada and Ukraine participate in a rapidly expanding global research field driven by interdisciplinarity and technological innovation. Their findings position Ukraine as an emerging actor in global STEM scholarship, while situating Canada as a mature system grounded in sustainability, inclusion, and the integration of Indigenous knowledge.

The following chapters translated these macro-level observations into pedagogical practice. Together they reveal that STEM is not a monolith but a living ecosystem: adaptable, participatory, and infused with local meaning. Whether manifested through humanitarian disciplines in technical universities (O. Hrechanovska, Chapter 2.1), through digital and analytical modeling with Maple (I. Shyshenko, T. Lukashova, & O. Pypka, Chapter 2.2), or through pedagogical experiments in teacher training (H. Rozlutska, S. Hirniak, & Ya. Petryna, Chapter 3.1), the concept assumes distinct yet interconnected forms.

What unites these efforts is a common belief that STEM education should cultivate both precision and empathy, merging scientific reasoning with humanistic reflection. As A. Yurchenko (Chapter 3.2) demonstrates, integrating project-based learning and digital visualization enhances not only professional skills but also teamwork, flexibility, and communicative awareness qualities that are indispensable in contemporary teacher education. Similarly, A. Melnyk (Chapter 3.3) demonstrates that STEAM-oriented vlogging bridges linguistic competence and creative self-expression, empowering future language teachers to view technology as a medium of inquiry and dialogue rather than mere instruction.

The fourth section extends this integrative vision toward specialized and value-oriented domains. A. Zhukova, M. Halchenkova, Ya. Dziuba and S. Demikhova (Chapter 4.1) address the formation of interdisciplinary thinking in military education, showing how the STEAM approach humanizes professional training in high-stakes environments. A. Truten and S. Tolochko (Chapter 4.2) connect STEM pedagogy with ecological literacy, emphasizing that environmental competence is not peripheral but central to the mission of 21st-century schooling. Their model demonstrates how project-based learning can instill responsibility, resilience, and ecological awareness among students.

Taken together, these chapters portray STEM education as a dynamic intersection of disciplines, values, and communities. It is both a mirror reflecting a nation’s development trajectory and a motor driving its renewal. In Canada, this renewal aligns with sustainability and inclusion; in Ukraine, it unfolds through creativity and reconstruction in the face of adversity. Both pathways, though different in context, converge on a shared educational philosophy: that knowledge must serve humanity.

2. Pedagogical Findings

The pedagogical insights derived from this monograph suggest an emerging paradigm that transcends the boundaries of traditional instruction. Across institutions and countries, the contributors highlight three converging trends: integration, personalization, and ethical innovation.

Integration manifests through the dismantling of rigid disciplinary borders. O. Hrechanovska's model of integrating humanities into technical education provides compelling evidence that creativity and ethical reasoning can enhance engineering training rather than distract from it. Likewise, the implementation of Maple in the mathematical preparation of teachers (I. Shyshenko, T. Lukashova, O. Pypka) exemplifies how digital tools expand conceptual understanding, linking abstract theory with practical modeling and data analysis. These approaches validate the premise that STEM learning is most effective when grounded in authentic inquiry and real-world problem-solving.

Personalization emerges through pedagogical models that acknowledge learners as co-creators of meaning. A. Yurchenko's digital visualization framework and A. Melnyk's STEAM-based vlogging approach each place the student at the center of the learning process, using technology to scaffold reflection, collaboration, and self-efficacy. These cases demonstrate that digitalization does not dehumanize education; rather, it opens space for voice, agency, and cognitive diversity.

Ethical innovation constitutes perhaps the most significant pedagogical insight. The ecological focus of A. Truten and S. Tolochko highlight that sustainability is not merely an add-on, but a fundamental pedagogical principle. Teaching students to design environmentally conscious projects, whether through robotics, urban planning, or data science, reframes STEM as education for care, not only for competence. Similarly, the integration of STEAM into military education (A. Zhukova,

M. Halchenkova, Ya. Dziuba, S. Demikhova) demonstrates that even highly structured learning environments can evolve into spaces that foster empathy, cultural literacy, and reflective practice.

From these examples arises a broader pedagogical pattern: STEM as transformation. It transforms the learner's mindset from one of consumption to one of creation, the teacher's role from transmitter to facilitator, and the institution's mission from credentialing to cultivating innovation. The Ukrainian and Canadian experiences affirm that transformation begins not with infrastructure, but with the pedagogue's capacity to connect disciplines, technologies, and values in purposeful ways.

3. Societal and Policy Dimensions

Beyond the classroom, STEM education exerts a profound influence on social cohesion, economic development, and policy formation. The comparative lens of this monograph allows us to see how these dynamics unfold differently yet complementarily in Canada and Ukraine.

In Canada, STEM policy has long been closely tied to national strategies for sustainability, equity, and reconciliation with Indigenous communities. Programs supporting underrepresented groups, particularly women and Indigenous youth, exemplify how inclusion can drive innovation. The integration of arts into STEM, widely adopted through STEAM initiatives, reflects a belief that creativity is not a luxury but a precondition for progress.

In Ukraine, the picture is defined by resilience and acceleration. Despite the devastation of war and the displacement of academic communities, Ukrainian educators have continued to digitize curricula, establish STEM laboratories, and engage students in project-based and socially oriented learning. The case studies presented in this volume demonstrate how universities and schools serve as laboratories of social reconstruction, where education acts as a stabilizing and forward-looking force.

Both contexts demonstrate that STEM education operates as a bridge between policy and practice. Its success depends not only on funding and infrastructure, but also on a shared cultural narrative that links scientific literacy to civic responsibility. The projects described by H. Rozlutska, S. Hirniak, & Ya. Petryna and A. Truten & S. Tolochko reveal how national standards for general and higher education can incorporate sustainability, teamwork, and digital competence as measurable outcomes. This alignment of pedagogy with policy represents a new stage in educational governance, one that treats innovation not as an external reform, but as a living process within institutions.

At a macro level, the monograph emphasizes the importance of cross-sectoral collaboration, where universities partner with industries, schools cooperate with municipalities, and research centers engage policymakers. The Canadian experience offers valuable lessons in systemic coordination, while the Ukrainian experience demonstrates that innovation can thrive even in decentralized, resource-limited settings. The comparative analysis, therefore, suggests that the strength of a STEM ecosystem lies not in uniformity, but in adaptive diversity – the ability to translate global trends into local relevance.

4. Future Directions

Looking ahead, several trajectories emerge from the comparative experience presented in this book. They concern not only how STEM education is taught, but how it is conceptualized as a social mission in an age of technological and ethical uncertainty.

First, the integration of Artificial Intelligence into educational design opens both opportunities and dilemmas. As digital tools become capable of generating, analyzing, and even simulating knowledge, the educator's role must evolve from controlling information to curating meaning. Future research should therefore explore the use of AI-assisted inquiry, multimodal assessment, and the ethical application of data analytics in STEM pedagogy. This direction aligns with Canada's strong focus on educational technology ethics and Ukraine's rapid adoption of AI-driven learning tools during wartime digitization.

Second, evidence-based evaluation of STEM outcomes deserves systematic attention. The studies presented in this monograph point to positive shifts in motivation, critical thinking, and professional readiness, yet they also reveal the need for longitudinal tracking. Future collaborations should develop unified indicators and digital dashboards that can visualize how STEM learning contributes to innovation, social cohesion, and sustainable development.

Third, teacher professionalization and digital inclusion must remain priorities. As shown by O. Hrechanovska, I. Shyshenko, T. Lukashova, O. Pypka, and A. Yurchenko, teacher education stands at the front line of innovation. However, educators require continuous support not only in mastering technologies, but in cultivating pedagogical ethics and intercultural sensitivity. The creation of open-access professional learning communities could serve as a shared Canadian–Ukrainian contribution to the global STEM teaching network.

Fourth, interdisciplinary research and policy dialogue should intensify. The ecological and social dimensions of STEM, explored by A. Truten and S. Tolochko, call for cross-ministerial cooperation: linking education, environment, economy, and innovation policies into coherent frameworks. The Sustainable Development Goals (SDGs) already provide such a platform; the task now is to embed them into curriculum design, teacher standards, and funding mechanisms.

Finally, the humanistic turn in STEM must continue. Technological progress without moral reflection risks alienation and inequality. As editors, we believe that the future of STEM education depends on restoring balance between innovation and empathy, between the algorithm and the conscience. Each chapter of this book, in its own way, points to the same conclusion: the more complex the technology, the greater the responsibility of the teacher.

5. Canada–Ukraine Partnership: Building a Shared Future

Throughout this collaborative endeavor, a vision has crystallized that STEM education can become a common language of reconstruction, resilience, and solidarity. The partnership between Canada and Ukraine, already active in research and higher education, offers fertile ground for advancing this mission.

Canada brings to the table its mature ecosystem of inclusive STEM programs, strong public–private cooperation, and a culture of reconciliation that connects technological progress with human rights and community development. Ukraine contributes creativity born of necessity, a vibrant academic culture capable of innovating under pressure, repurposing limited resources, and turning crisis into experimentation.

We envision several practical directions for continued cooperation:

- Establishing a Canada–Ukraine Digital STEM Hub, a transnational platform for joint courses, teacher training, and research dissemination.
- Creating joint grant schemes for applied research in sustainable technologies and education innovation.
- Launching exchange programs for young educators and graduate students, enabling them to co-develop STEM curricula focused on reconstruction, energy transition, and social entrepreneurship.
- Promoting joint scholarly publishing bilingual editions and open-access repositories that strengthen the visibility of Ukrainian research internationally.

Such collaboration would not only benefit the two nations but also contribute to a broader global learning commons – a network of educators and researchers dedicated to advancing STEM for peace, equity, and sustainability. In this sense, the Canada–Ukraine partnership embodies the very spirit of STEM: curiosity, cooperation, and creative problem-solving in service of humanity.

6. Closing Reflection

In concluding this monograph, we return to the question that guided our editorial work: What does STEM education mean today? The answer, after traversing so many perspectives, remains profoundly human. STEM is not merely a set of disciplines or technologies; it is a way of thinking about the world, analytical yet imaginative, data-driven yet value-oriented.

In Canada, STEM education reinforces a long-standing tradition of learning as a community-building endeavor, where inclusion and sustainability define progress. For Ukraine, it signifies both recovery and hope, a means of rebuilding not only infrastructure but trust, identity, and purpose. Together, these narratives affirm that education is the most enduring form of resilience.

The voices represented in this volume, educators, researchers, and innovators, remind us that the future will not arrive on its own. It must be designed, debated, and built through collaboration. Each laboratory, classroom, and digital workspace becomes a site of reconstruction, where the next generation learns to connect logic with compassion, precision with imagination.

As editors, we view this book as both a documentation and an invitation: a record of what has been achieved, and an invitation to continue the dialogue. The transformation of education is not a task for one nation or discipline; it is a shared journey toward a more sustainable and humane world.

STEM Education in Canada and Ukraine: Transformations, Innovations, and Pathways for Sustainable Development closes not with a full stop but with an open horizon, one that extends from classrooms to laboratories, from policy tables to communities. In that horizon lies the most powerful equation of all: knowledge multiplied by empathy equals progress.

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