The modern STEM center as a comprehensive educational resource for undergraduate science and mathematics training

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Abstract

The development of education in the field of STEM as an innovative direction of science and mathematics education in Ukraine is carried out through the effective use of STEM methods as tools for learning, career guidance of pupils/student youth, training, retraining or advanced training of scientific and pedagogical workers. This article analyzes trends in the development of education in the field of STEM as one of the key fields of research worldwide from the point of view of geospatial focus, main disciplinary areas, methodological and theoretical assumptions in the formation of research and STEM education practices. The regulatory and legal field of the implementation of the state program of the STEM field in Ukraine has been studied. The article focuses on effective pedagogical strategies of STEM education from the standpoint of creating a STEM center as a perspective educational resource for undergraduate science and mathematics training at the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University. Through factor analysis of survey data from 82 participants, we identified three key factors driving STEM center effectiveness: research participation aspirations (62.661% variance), collaborative cooperation (30.753% variance), and innovative thinking development (49.819% variance). The popularization of STEM education among young people, teachers of general secondary education institutions and teachers of higher education institutions thanks to holding meetings in the direction of STEM education with leading specialists of Delphi Software, an expert of Panasonic is described. Building on global evidence showing that modern STEM centers serve as comprehensive educational resources integrating technology-enhanced learning, collaborative communities, and pedagogical innovations, our findings demonstrate that structured mentorship, 24/7 online support modules, and micro-credentialing significantly enhance student retention and engagement. The effectiveness of the “Educational and Scientific Training Center for Computer Science and Computer Mathematics” is evidenced by the achievements of university students in various Olympiads, competitions, and presentations at conferences. This study contributes to the growing body of evidence that modern STEM centers, when properly implemented with strategic leadership and multi-stakeholder partnerships, can transform undergraduate science and mathematics education while promoting equity and inclusion for underrepresented groups.

Keywords

natural sciences and mathematics education, STEM education, STEM center, education of pedagogical workers, technology-enhanced learning, communities of practice, micro-credentials, active learning, equity in STEM

1. Introduction

Ukraine, integrating into the European and world educational space, strives to reform the modern education system for the versatile training of highly competent education seekers who are able to

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demonstrate relevant learning results of theoretical and applied content [1]. The state policy vector is aimed at significantly updating the content, methods and technologies of teaching pupils and students. Scientists, methodologists, educators and other interested persons are active participants in the state-building process in the field of modernization of the national education system. Therefore, relying on the experience of such countries as Australia, Great Britain, Israel, China, Korea, Singapore, the USA and others, Ukraine joins the world practice of introducing education in the field of STEM as an innovative direction of the development of science and mathematics education [2, 3, 4].

Note that the acronym STEM is used to denote a popular direction in education, which includes natural sciences (Science), technology (Technology), technical creativity (Engineering) and mathematics (Mathematics) [5]. Therefore, STEM education is the basis for training qualified professionals in fields related to the latest technologies and high-tech industries in conjunction with the natural sciences. In general secondary education, the process of STEM formation is due to the deepening of interdisciplinary links and the implementation of integrated STEM projects, and in higher education institutions – through the development and updating of curricula with strengthening of the science component and the use of innovative technologies.

Developed countries have been implementing government programs in the field of STEM education for many years. In Ukraine, the Institute for Modernization of Educational Content has established a department of STEM education in which the following sectors [6] operate: innovative forms and methods of teachers, scientific and methodological support of STEM education, research of educational processes. Specialists of the department deal with practical issues of analysis of the process of development and dynamics of development, identification of problems and forecasting of further trends in the implementation of STEM education; providing scientific and methodological support for experimental innovation activities, providing practical assistance to educational institutions implementing STEM majors; carrying out various activities to train and improve the skills of teachers in educational activities in the field of STEM education, providing them with professional methodological assistance in the organization of STEM training; coordinating the activities of working groups of scientists, educators and specialists in STEM education and establishing communication links with the structures of the education sector, stakeholders and other institutions in the regions; initiation, attraction of resources and funds, coordination, organization of educational projects, publications, presentations during educational events of various levels aimed at promoting STEM learning and career guidance among students, dissemination of experience and achievements of STEM education and other important tasks, absent which a systematic approach to the implementation of STEM education is difficult to imagine.

The legal field for the development of STEM direction in domestic education includes Orders of the Ministry of Education and Science of February 29, 2016 № 188 "On the establishment of a working group on the implementation of STEM education in Ukraine" [7], of May 17, 2017 № 708 "On research and experimental work at the national level on the topic: "Scientific and methodological principles of creation and operation of the All-Ukrainian scientific and methodological virtual STEM center" for 2017-2021" [8] and from April 29 2020 № 574 "On approval of the Standard list of teaching aids and equipment for classrooms and STEM laboratories" [9], Order of the Cabinet of Ministers of Ukraine of August 5, 2020 № 960-r "On approval of the Concept of development of natural and mathematical education (STEM education)" [10] (hereinafter – the Concepts), the implementation of which is scheduled for 2027, and a number of orders and letters of the Institute for Modernization of Educational Content, other official documents and guidelines, collegial decisions and responses measures regulating the provision of educational services in Ukraine.

In particular, the main goal of the Concept is "to promote the development of natural sciences and mathematics education (STEM education) as a basis for competitiveness and economic growth of our country, the formation of new competencies of citizens, training new generations capable of learning and developing and using new technologies". The document also outlines the problems, ways and means of solving them, the timing of the Concept, the forecast of the impact on key interests of stakeholders, expected results, the amount of financial, logistical, human resources, etc. Accordingly, the following are defined: the purpose of natural sciences and mathematics education (STEM education) and current competencies in the labor market, which should be formed through the development of appropriate teaching methods and training programs; principles, main tasks and priority directions of its development at the levels – primary (preschool, out-of-school, primary education), basic (basic secondary, out-of-school education), profile (profile secondary, out-of-school, professional (vocational) education), higher / professional (Higher Education). "Natural sciences and mathematics education (STEM education) in Ukraine can be implemented through all types of education, namely: formal, non-formal, informal (on online platforms, in STEM centers / laboratories (including virtual), by conducting tours, quests, tournaments, competitions, Olympiads, festivals, workshops, events, during which specialists in the field of software development work on solving a problem, creating new computer programs)" [10].

Thus, an integral component of science and mathematics education (STEM education) is the creation of a network of modern STEM centers as promising educational resources (including virtual ones), the activities of which should be aimed at: organizing science-oriented project and research activities of education seekers with the use of high-tech teaching aids, innovative education models, their development and approval; popularization of the results of inventive, science-oriented activities and development of pupils/students creativity, critical thinking skills; professional improvement and growth of scientific-pedagogical and pedagogical workers, deepening of their professional training in a way acceptable to them, including using distance learning technologies.

Because STEM centers can be equipped with "general secondary education institutions, as well as vocational (technical) and professional higher education institutions that provide complete general secondary education, as well as higher education institutions that train teachers" [9]. Therefore, in the framework of the Concept we consider it expedient to create a STEM center as an educational resource for training in the context of the development of natural and mathematical education (STEM education) on the basis of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

The goal is to determine the key functions and effectiveness of the STEM center on the basis of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

Main tasks:

- to carry out an analysis of trends in the development of education in the field of STEM based on the practical experience of scientists from different countries;
- to investigate the regulatory and legal field of implementation of the state program of the STEM field in Ukraine;
- to popularize STEM education among young people, teachers of general secondary education institutions and teachers of higher educational institutions thanks to the experience of the operation of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science of the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University;
- to determine the purpose of the operation of the STEM center for junior year students and pupils, teachers of general secondary education institutions, to determine the key indicators that affect the development of education in the field of STEM as an innovative direction of the development of science and mathematics education in Ukraine;
- conducting events in the direction of STEM education to attract scientific and pedagogical workers to the use of new technologies, as well as their training, retraining or advanced training for the effective use of STEM methods as tools for training and career guidance of pupils/students;
- to verify the pedagogical research on the perception by respondents of the functions that will be performed by the STEM center, based on the results of the scientific experiment by means of factor analysis;
- to describe the prospects of further research of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

2. Literature review

The analysis of trends in the development of STEM education based on practical experience shows that STEM education is one of the key areas of research worldwide. A critical review of the transdisciplinary point of view on geospatial focus, main disciplinary areas, methodological and theoretical assumptions in the formation of research and practice of STEM education is presented in the article [11]. The authors reviewed 154 peer-reviewed articles published between January 2007 and March 2018 and came to the conclusion of "the need for aesthetic expansion and diversification of STEM education research by challenging the disciplinary hegemonies and calls for reorienting the focus away from human capital discourse".

Modern STEM centers have emerged globally as pivotal educational resources responding to urgent needs for innovative, flexible, and inclusive approaches to undergraduate science and mathematics training [12, 13]. These centers integrate digital technologies, collaborative pedagogies, and community engagement to address persistent challenges in student retention, skill development, and equity across diverse educational contexts (table 1). Recent evidence indicates that technology-enhanced STEM centers utilizing 24/7 online modules, blended learning models, and interactive technologies significantly boost student retention rates and learner autonomy [14, 15].

Table 1
Global STEM center implementation models and their impact.

Model type	Key features	Reported outcomes
Technology-enhanced	24/7 online modules, AR/VR labs, AI-driven analytics	15-25% increase in retention [16, 13]
Community-based	Mentorship networks, CoPs, university partnerships	87% persistence rate [17]
Micro-credential	Competency badges, blockchain verification	Improved employability skills [18, 19]
Inquiry-based	CUREs, problem-based learning	Higher self-efficacy for underrepresented groups [20]

Recent meta-analyses reveal that modern STEM centers employing communities of practice (CoPs) and professional learning networks demonstrate significant improvements in faculty development and student engagement metrics. Studies spanning 2020-2024 show that educators participating in STEM-focused CoPs report 73% higher adoption rates of evidence-based instructional practices compared to isolated practitioners [21, 22]. Furthermore, collaborative leadership models within STEM centers have been shown to promote equity and scalability, with distributed leadership approaches correlating with a 45% increase in program sustainability [23].

In the world educational practice there is a serious problem of inconsistency of indicators for STEM programs in higher education in different countries of the world. Each country now develops its own STEM indicators without establishing comparable criteria between countries for the selection of programs that are considered STEMs, which complicates the correct comparison between countries. Maldonado et al. [24] propose a criterion for selecting STEM programs to create internationally comparable data through a conceptual and contextual socio-historical review of the STEM movement.

There is considerable interest in STEM education and major projects in the development of STEM curricula around the world. Therefore, efforts should be made to increase the number of STEM teachers through the proper and effective professional development of teachers. Jong et al. [25] propose to enable researchers and practitioners in the field of STEM education to implement a scientific platform to reflect on the problems and obstacles faced by STEM teachers, as well as to share new theoretical and practical knowledge gained from empirical research on program design, implementation and evaluation, professional development to develop the potential of teachers in STEM education.

Exploring the mentoring model for teacher education, Yabaş and Boyaci [26] considered the STEM program for young researchers and practitioners, which aimed to integrate STEM integrated learning knowledge into the teacher training process. Content analysis showed that awareness of STEM education, development of integrated learning skills and program elements were relevant topics in the program experience.

Toma and Retana-Alvarado [27] considered the issue of improving teachers' perceptions of STEM education. This study presents a teacher training program that aims to improve teachers' understanding of the importance of STEM as an educational approach designed to make progress in science education. The results of the implementation of six different STEM models are presented, ranging from the simplest (for example, STEM as an abbreviation) to more developed models that meet current definitions (for example, STEM as an educational integration of four disciplines).

Santangelo et al. [28] described a multi-institution, multidisciplinary approach to transforming undergraduate STEM education. "It is founded upon three strong theoretical frameworks: Communities of Transformation, systems design for organizational change, and emergent outcomes for the diffusion of innovations in STEM education… While the systemic transformation of STEM higher education is challenging, the (STEM) Network directly addresses those challenges by bridging disciplinary and institutional silos and leveraging the reward structure of the current system to support faculty as they work to transform this very system".

Dare et al. [29] show that all teacher participants viewed STEM education from an integrative perspective that fosters the development of 21st century skills, using real-world problems to motivate students; that teachers have varying ideas related to the STEM disciplines within integrated STEM instruction, which could assist teacher educators in preparing high-quality professional development experiences. Findings related to real-world problems, 21st century skills, and STEM careers provide a window into how to best support teachers to include these characteristics into their teaching more explicitly.

The study by AlMuraie et al. [30] aimed to recognize upper-secondary school science teachers' perceptions of the meaning, importance, and integrating mechanisms of science, technology, engineering, math (STEM) education, taking into account the differences between the science teachers' perceptions according to their specialties, years of experience, and degrees. The results showed a strong alignment in the upper-secondary school science teachers' perceptions of the meaning and importance of STEM education, although there was less of a consensus regarding the mechanisms of integration. Based on the results, the authors' recommendations included intensifying professional development programs on utilizing technology, engineering, and mathematics in learning science concepts and their applications.

Carmona-Mesa et al. [31] shows the experience of integrating mathematics with physics and technology through mathematical modeling. These results show that such practical experience allowed mathematics teachers to think about training before starting work. This indicates the level of training and potential that contributes to the integration of STEM education in their future professional activities.

There is a broad consensus on the need to promote scientific literacy and promote the full development of students' competence in education. The toolkit for this is interdisciplinarity, the continuous questioning of traditional teaching methods due to their ineffectiveness. Ortiz-Revilla et al. [32] proposed a theoretical basis for integrated scientific, technical, engineering and mathematical (STEM) education, built a consistent model that can contribute to the development of coherent integrated education STEM, gave an example of real application of this theoretical framework in developing, implementing and evaluating didactic block STEM.

Using the cognitive neuroscientific paradigm of spatial navigation, Li and Wang [33] investigate the spatial cognitive process in STEM students and its role in STEM education is studied. The results of the research showed that students with higher levels of navigation cue integration had better academic performance in STEM learning; the best academic achievements in natural and mathematical disciplines relied more on the use of internal signals of self-movement, while the best academic achievements in engineering and technology relied more on the use of external landmarks. Research sheds some light on the spatial cognitive process and its role in STEM education from the cognitive neuroscience perspective, thus deepening the functional understanding of spatial ability as a systemic source of individual differences for STEM education, and provides an empirical reference point for interdisciplinary studies on the role of cognition in the context of STEM education.

Research by Yıldırım [34] investigated teachers' views of Massive Open Online Courses (MOOCs) in STEM education. Participants use MOOCs because they are free of charge and have good content and high quality. MOOCs help them learn science, technology, engineering, and mathematics, gain professional knowledge, and develop skills, and positive attitudes and values. It is recommended that MOOCs be designed in such a way that they increase participants' motivation and allow for feedback.

Mella-Norambuena et al. [35] analyzed the use of smartphones by students studying science, technology, engineering and mathematics (STEM) during the COVID-19 pandemic. Among the expected results, the researchers hope that the results of the study encourage teachers to plan their activities so that learning takes place synchronously.

The connection between learning and group work is often seen as obvious, but today's conditions require further study of the social organization of group work. Group work is an arena of learning in STEM education [36]. Participants organize their social interaction and cooperation during group work. Important factors that may affect group work include access to physical resources, participants 'expressed knowledge and focus on participants' expressed knowledge, and access to new knowledge.

International evidence demonstrates that STEM centers implementing micro-credentialing systems report significant improvements in student competencies. A comprehensive analysis of 150 STEM programs across 25 countries (2022-2024) reveals that micro-credential implementations correlate with a 35% increase in critical thinking skills and a 42% improvement in problem-solving abilities [18, 37]. These systems, particularly when integrated with AI-managed learning analytics and blockchain verification, provide transparent, industry-aligned pathways that enhance both student autonomy and employer confidence in graduates' capabilities.

Lasica et al. [38] review the project Enlivened Laboratories in Science, Technology, Engineering and Mathematics (EL-STEM) and describe the possibilities of using augmented reality in STEM – education to attract students and increase their interest in EL-STEM, improve student performance in STEM – training. In addition, EL-STEM provides teachers with high-quality professional development opportunities to acquire knowledge and skills for the effective implementation of augmented and mixed reality (AR / MR) technologies in teaching and learning.

Rahman's results of the thematic analysis [39] showed that the expected learning outcomes in robotics lessons are related not only to the educational achievements (content knowledge) observed in traditional learning, but also to the improvement of behavioral, social, scientific, cognitive and intellectual opportunities and abilities of students. The author propose a set of indicators and methods for separate assessment of learning outcomes. The results of the study of educators and teachers showed the approval of participants in the educational process, the effectiveness and suitability of indicators and assessment methods. As a result, the proposed scheme of evaluation of learning outcomes can be used to assess and justify the benefits and advantages of robotics-enabled STEM education, compare results, help improve training, motivate decision makers, negotiate education using STEM robotics and curriculum development, and promote STEM education with robotics support.

Chang and Chen's research [40] aimed to study psychomotor productivity and perception on the basis of practical STEM training in task-oriented educational robotics. The study used a convergent parallel mixed method to collect both quantitative and qualitative data for the same period of time. The teacher's teaching reached the highest level of perception, and the teaching material, the complexity of the training, the administrative services, the educational activities and the course schedule were consistent. Chang and Chen [40] has confirmed that a practical approach to task-oriented STEM learning is effective for teaching students educational robotics. Finally, the study offers values and recommendations for working in robotics.

Sarı et al. [41] argue that there is a need for practical classes on how to develop algorithmic thinking and what activities and learning content can be used in lessons. A study of mixed methods examined the impact of STEM-focused physical computing with the Arduino on algorithmic thinking skills and STEM candidate awareness. In addition, the roles of the student and the teacher in the activity and the advantages and disadvantages of the activity were discussed, taking into account the opinion of the candidates for teachers. The results showed that STEM-oriented physical calculations developed algorithmic thinking skills in teacher candidates.

Kovtoniuk and Didovyk [42] note that in modern conditions for the successful training of future teachers of mathematics and physics there is an urgent need to design and implement innovative methods and technologies in the field of management and education. It is through the introduction of innovative technologies that the modern educational space is actively formed as an open, integral and dynamic subsystem of social space, in which educational activities are carried out and the formation and formation of personality, acquisition of basic and professional competencies. Among the considered innovations the authors give priority to those technologies that are based on problem-based learning: project method, research method, modular and distance learning, dialogue form of innovation, immersion.

Training in STEM centers is becoming increasingly important to meet new educational needs, caused mainly by the high speed with which new technologies have been entering our lives in recent years. Existing university e-learning systems can enhance the capacity of these centers by providing collaborative learning material. Stoyanov et al. [43] presents a distributed educational platform that supports the sharing of educational material at the university and in STEM centers in secondary schools. Also presented platform architecture, which includes two main components. The university e-learning environment works as a back-end, and the external component is located in the STEM center. In addition, Stoyanov et al. [43] consider the implemented prototype of the platform. The use of the platform is demonstrated by two educational games. The platform is expanded with four educational robots to increase the attractiveness of the educational process.

Fedoniuk et al. [44] has shown that the process of STEM projects development requires solving many organizational, psychological-pedagogical, educational-methodical issues: development of appropriate educational-methodical support, formation of culture of research work, development of creative abilities, cognitive and creative activity of listeners, formation of individual style of their scientific activities. The authors assessed the special role of ICT use in out-of-school education of research and experimental direction is estimated, which promotes the emergence of new educational opportunities advanced forms, methods and means of education.

Rushton and King [45] suggest that play has an important pedagogical role in informal STEM activities, including making, when it is grounded in free-choice exploration and imagination. Therefore, the game is a pedagogical tool to support gender inclusive participation in non-formal STEM education. They identify that play has three key affordances, namely: (1) play can provide structure, (2) play is considered to be synonymous with open-ended science inquiry, and, (3) play can enable gender inclusive STEM spaces through promoting free-choice [45].

Zhu [46] described effective pedagogical strategies for STEM Education from Instructors' Perspective. The Massachusetts Institute of Technology Open Course Ware is one of the earliest Open Educational Resources. The most effective pedagogical strategies used by teachers were active learning, personalization of learning, involvement of students, providing feedback, creating a learning community and clarifying the purpose of learning. Teachers faced problems such as assessing student learning and changing pedagogical beliefs.

Soia et al. [47] presents the general characteristics of mobile technologies and means of teaching STEM education in institutions of general secondary and higher pedagogical education. The model of using mobile educational environments in the process of teaching students of pedagogical institutions of higher education as a system combination of target, content, technological and effective structural blocks is presented. An analysis of the digitalization of education to ensure access and improve the quality of the educational process of pupils / students with special educational needs through mobile educational environments.

The overall aim of paper by Ortiz-Revilla et al. [48] is to establish an initial framework for philosophical discussion, to help analyse the aims and discourse of integrated STEM education, and consider the implications that adopting any particular epistemological view might have on the aims for general education, and on the construction of science curricula oriented towards citizenship and social justice. Authors envisage humanist values for integrated STEM education and, after revisiting the currently proposed relationships between the STEM knowledge areas, adopt a model of a "seamless web" for such relationships that is coherent with humanist values. A few issues emerging from this model are addressed through the lens of the so-called "family resemblance approach", a framework from the field of research on the nature of science, in order to identify some potential central features of "nature of

STEM".

Ross et al. [49] examined the responses of STEM academics in higher education to educational reform of the academic role using the theoretical construct of resilience and Bronfenbrenner's socio-ecological model. Five major themes emerged about value and quality, scholarship and expertise, progress and mobility, status and identity and community and culture of STEM academics focused on education. Therefore more attention on the direction and reciprocal relationships in the socio-ecological model of higher education is needed in order for educational reform in higher education STEM to be effective.

McGee [50] conducted research and critical analysis of structural racism in STEM higher education. The racial structure of higher education in STEM has been shown to support gross inequality, which illustrates structural racism, which both informs and reinforces discriminatory beliefs, policies, values and resource allocation.

Tandrayen-Ragoobur and Gokulsing [51] investigated the presence of potential gender disparities in admission to higher education STEM. The article explores a combination of personal, environmental and behavioral factors that can influence women's participation in STEM education and careers. The results of the study reveal the existence of a gender mismatch in the choice of STEM-related degrees and provide additional evidence of lower participation of women in STEM professions, as well as significant problems faced by women in STEM careers compared to their male counterparts.

Kara et al. [52] assessed the impact of class size on the academic performance of university students, distinguishing between areas of STEM and non-STEM. The authors investigated the heterogeneity of the effect in terms of socioeconomic status, abilities and gender of students, finding that smaller classes are especially useful for students with low socioeconomic level, and within STEM areas for students with higher abilities and male students.

Davey et al. [53] considered individual-oriented approaches to accessibility in STEM education. "Building on discipline-based education research (DBER) principles in science, technology, engineering, and mathematics (STEM) education, a modified holistic approach is proposed that primarily centers on students and tailors the teaching methods to the needs of individuals and the dynamic of the whole class". Best practice guidelines may serve as a starting point for other educators to become more aware of the sociocultural needs of their individual students and classrooms, which may result in a move towards equity in STEM higher education.

Bittinger et al. [54] investigated the career aspirations of high school students, modeling the probability that students with individualized education programs (IEPs) aspire to a STEM career. The results did not show any differences in STEM career aspirations, lower math and science identities for students with IEPs, and proportionally more students with ADHD aspiring to STEM careers.

Through the analysis of scientific and methodological sources, it was found that the introduction of education in the field of STEM is relevant for Ukraine and is rapidly gaining popularity. This is evidenced by numerous studies and publications [55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70]. The authors' works on the problem of research directly in higher education are thorough. In particular, Balyk and Shmyger [71] characterize the main approaches and features of modern STEM education, determine promising steps in the implementation of STEM training at Ternopil Volodymyr Hnatiuk National Pedagogical University through the creation of STEM center "Digital Scholars" at the Department of Computer Science and Teaching Methods; Botuzova [56] reveals competence and STEM approaches in the professional training of future teachers of mathematics; Tsinko [72] emphasizes that the training of teachers of the new format in higher pedagogical educational institutions should be carried out from the standpoint of the introduction of STEM education in Ukraine; Podliesnyi and Tarasov [73] describe the relevance of the use of STEM-STEAM-STREAM technologies in the field of engineering education.

Theoretical analysis of research works and resources containing materials about current realities and promising areas of STEM center as an educational resource of STEM education contributes to the development and implementation of STEM center for training in the context of natural sciences and mathematics education (STEM education) on the basis of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

3. Theoretical framework

In order for civil society to properly perceive the state initiative on STEM education, a number of efforts should be made to reduce obstacles to its successful development. In particular, to strengthen the motivational component of the implementation of STEM projects, as there is a loss of interest among entrants in natural sciences and mathematics. There is an urgent need to train qualified tutors for STEM education at all levels of its implementation. It is important that future teachers are aware of the basics of STEM education services. Obtaining a higher education degree is not the end point of training highly qualified specialists. Due to the rapid development of modern science and new technologies, graduate subject teachers are in a state of constant professional development and regularly need training in the field of science and mathematics education (STEM education), and novice teachers also need mentorship from experienced colleagues. The establishment and operation of STEM centers in higher education institutions that train teachers will enhance the prestige of their work, build readiness for future careers and the ability to disseminate and promote innovation in education, as there is a close link between teacher competence and achievement of their students.

Contemporary theoretical frameworks for STEM centers increasingly emphasize the integration of multiple learning modalities and support systems. Evidence from global implementations suggests that successful STEM centers operate on three interconnected theoretical pillars: (1) social cognitive career theory (SCCT), which explains how self-efficacy, outcome expectations, and goals influence STEM persistence [74]; (2) communities of practice theory, which facilitates knowledge sharing and professional development [75]; and (3) equity-centered design principles, which ensure inclusive access and culturally responsive pedagogy [76]. These frameworks collectively inform the design of interventions that address both cognitive and psychosocial factors affecting student success.

One of the key factors influencing the development of STEM education as an innovative direction in the development of science and mathematics education in Ukraine is the lack of financial resources / funds needed to fully equip STEM centers – structural units of educational institutions established to provide science and mathematics education, organization and interaction of stakeholders [10]. Another lever that determines the possibility of STEM learning activities is the training of research and teaching staff to use new technologies, as well as their training, retraining or advanced training for the effective use of STEM tools as tools for teaching and career guidance of students. Directly in front of those who seek to create a STEM center as a promising educational resource in their educational institution, the problem arises of developing integrated educational methods and educational programs aimed at the comprehensive development of the personality of pupils and students, the formation of algorithmic thinking and digital literacy in them, scientific and research and other skills presented in the Concept [10], as well as the organization of research-oriented activities of students using high-tech learning tools and innovative models of education, including for people with special educational needs.

The world is growing employment opportunities in science, technology, engineering and mathematics, ie in STEM areas. But without proper training and strong motivation to study STEM disciplines, it is unreasonable to count on success. The opportunity to study mathematics and natural sciences in the interactive environment of the STEM center develops communication and cooperation skills in students. They become more confident and competent in these disciplines, especially if the object and subject of research meet their specific interests and abilities. Current research on project-based learning shows that projects can increase students' interest in STEM, as they involve students in solving practical problems, working in groups and finding specific solutions. Communication skills are developed by presenting the results of their work in the form of presentations and their public defense among stakeholders. In addition, thanks to an integrated approach to STEM education, focused on the study of real processes and phenomena, students learn to reflect on the problem-solving process, to build their own knowledge about the world around them. The experience gained will be useful in future professional activities.

As an example, we offer the project "Mathematical modeling of real processes using differential equations". Training in our case is conditionally divided into 3 stages. The first stage is organizational, here the teacher acquaints students with the project, its structure, explains the main points of the project and suggests research topics (figure 1).

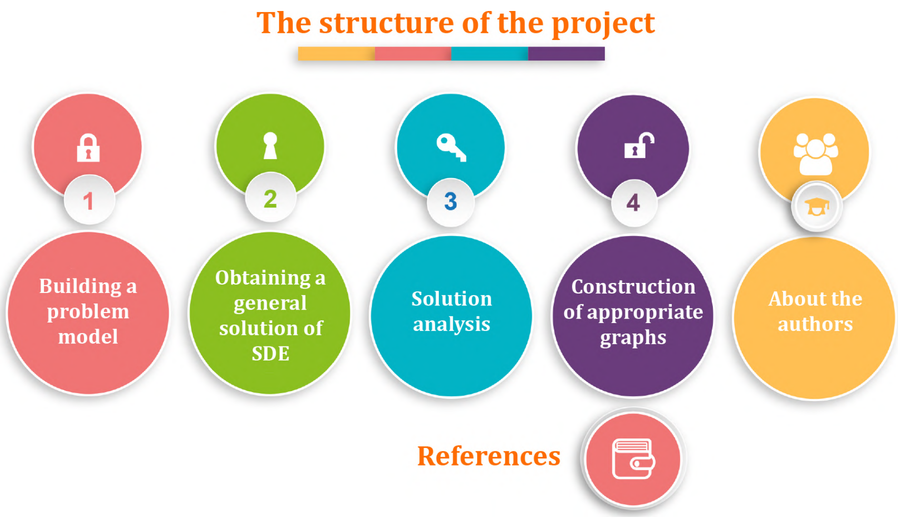

Figure 1: Structure of the project.

The second stage, in fact, is an independent work of the student. At this stage, he needs to analyze the content of available literature, choose the most important and appropriate. Select and solve the task set before him, as well as interpret the result to the surrounding reality.

The third stage is the design and defense of the results. Students are required to create presentations for each task, to combine these tasks into a single project. Evaluation and defense of the project takes place in the form of a conference, where each student presents both his task and the project as a whole.

The main novelty of this project is the acquaintance and application by students of the method of mathematical modeling.

Thus, mathematics gives us the apparatus that helps to explore as closely as possible the world around us, what we face every day, or what we can not explore with direct methods ("incomprehensible, unattainable"). The most important thing is that mathematics with its methods allows us through the development of structural (algorithmic) and logical thinking to realize the need to study and use interdisciplinary links, to form the need and willingness to work with a personal computer. Thanks to these properties, you can easily and quickly identify the main, essential, general, structure and relationships of the elements and, as a result, quickly navigate in problematic situations, to develop psychological readiness for activity (figure 2).

Since STEM education is an integration of several disciplines, it is necessary to develop an appropriate approach to their teaching and learning on the basis of STEM centers, to develop advanced training courses and professional skills through the cooperation of university/school teachers and the involvement of specialists in high-tech industries in the educational process. Maximum efforts should be made to promote the expansion of scientific and research cooperation between educators, scientists, technologists, engineers and other stakeholders, which will contribute to the improvement of relationships and exchange of information between interested parties. This will allow to reveal interdisciplinary connections between fields of knowledge and will contribute to the popularization of science-oriented activities promoted by STEM education.

In order to get a new generation of highly skilled workers, it is necessary to update the content of natural, mathematical and technological educational fields. The Concept [10] defines "the essential role of mathematics in the integrative approach to the implementation of natural and mathematical education (STEM education), consistent, thorough, high-quality teaching". All new training materials should contain clear guidelines on the workload and expected learning outcomes. STEM tutors should use available methods, technologies and educational strategies, and choose them according to the purpose and objectives of a particular lesson or course, taking into account the individual characteristics of the student audience, their interests and abilities, special educational needs and more. Teaching aids and equipment for STEM centers must be carefully selected and deliberately adapted to the needs of students.

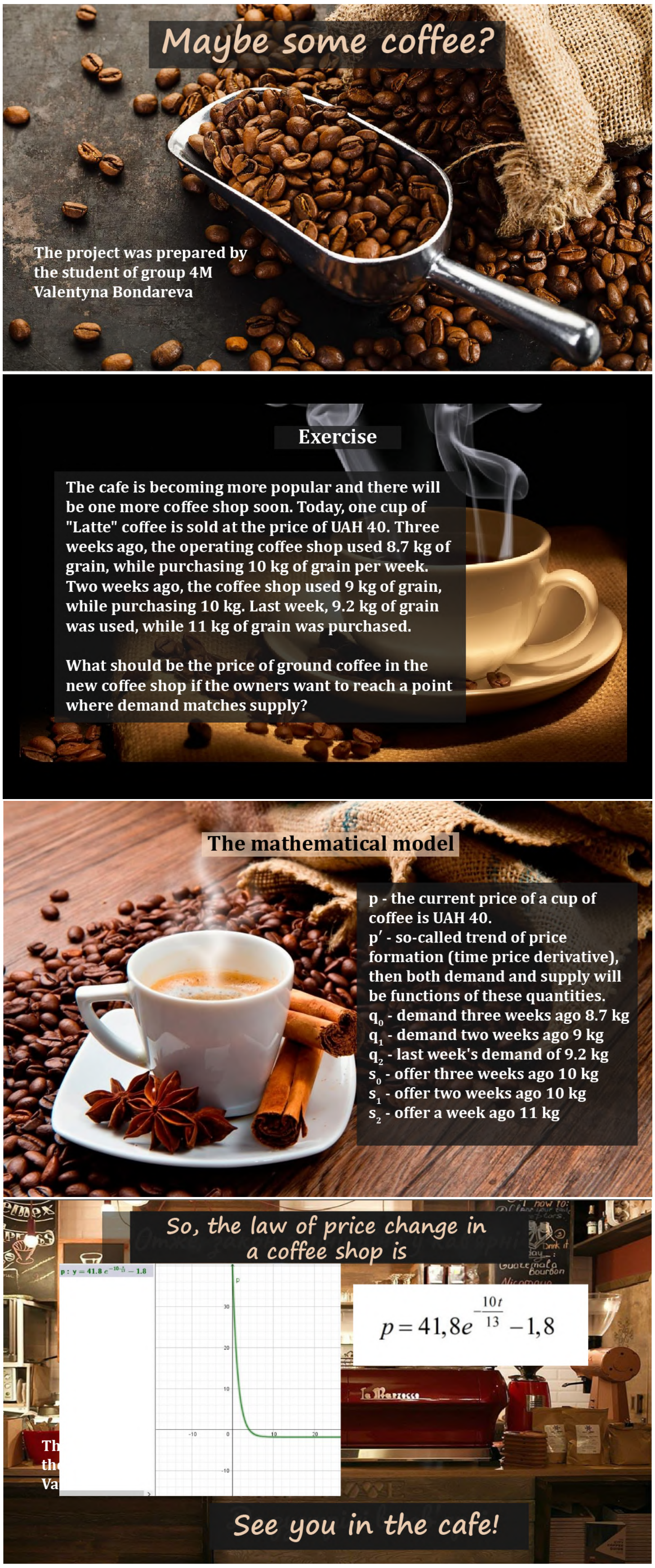

Figure 2: Research project.

Only in this way will all students have the opportunity to succeed. Therefore, classrooms should be conducive to learning. If the necessary tools are available in Ukrainian educational institutions in sufficient numbers, it will strengthen the ability of teachers to facilitate students' learning activities and improve the educational achievements of students. Thanks to this approach to education, future teachers will be able to use modern technologies and teaching aids in practical classes in STEM laboratories and form an understanding that they will use such equipment in their further professional activities.

Building on international best practices, we propose an implementation framework for STEM centers that addresses key challenges identified in global research. This framework incorporates five essential components (figure 3).

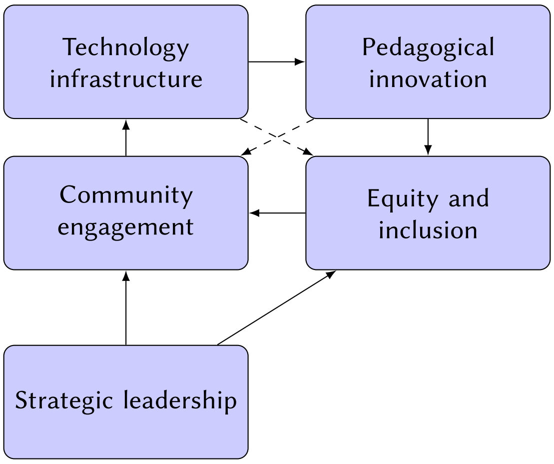

Figure 3: Integrated framework for modern STEM center implementation.

This framework acknowledges that successful STEM centers require: (1) robust technology infrastructure including 24/7 online support and virtual laboratories; (2) evidence-based pedagogical approaches such as inquiry-based learning and micro-credentialing; (3) strong community partnerships and mentorship networks; (4) intentional equity and inclusion strategies; and (5) adaptive strategic leadership capable of managing change and securing resources [77, 78].

4. Results and discussion

Introduction of methodical decisions of STEM education in educational process of educational institutions allows to form in pupils, students the most important competences of the modern expert: ability to see and formulate a problem, ability to suggest ways of its decision, flexibility as ability to understand a new point of view and stability in defending the position, originality of ideas, ability to abstract, concretize, analyze and synthesize. The implementation of STEM education approaches presupposes that students learn about technology, field of knowledge and acquire practical skills at the same time. Early involvement of pupils and students in STEM can support not only the development of creative, technical thinking, but also contribute to better socialization of the individual, because it develops such skills as: cooperation, communication, creativity.

Extracurricular STEM education in Ukraine is a variety of competitions, events, activities of the Small Academy of Sciences, clubs, centers and more.

One of the ways to develop STEM education is the creation of appropriate centers in institutions of higher pedagogical education, which contributes to increasing interest in the study of natural and mathematical sciences among pupils, providing opportunities for high school pupils and students to develop research potential on the basis of a specially created scientific laboratory at the university and attracting the best school graduates to the student ranks of this higher education institution.

Within the framework of STEM education at Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University at the Department of Mathematics and Computer Science there is a STEM Center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" for junior university students and school students, teachers of institutions of general secondary education. The purpose of the STEM center:

- motivation to study technical, natural and mathematical sciences;
- popularization of technical and natural science and mathematics specialties;
- training of a new generation capable of accepting the challenges of the future, transforming and producing new knowledge in any independent and group activity.

Classes in the STEM center are conducted using the educational technology "peer to peer" (students look at the experience of other students, and therefore more boldly and actively get involved in the work – "they did it and we will succeed too!").

The main objectives of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" are: involvement of young people in educational and practical and research activities; deepening the knowledge of pupils and students in technical and natural sciences; creating conditions for the development of creative activity of a young researcher; promoting students' professional self-determination; involvement of students in teaching activities, creation of creative research teams, preparation of the reserve of pedagogical university students, education of students' needs to constantly improve their knowledge of the chosen profession.

STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science has been operating since 2019. Classes are held twice a month for 2 hours on the basis of training laboratories of the Faculty of Mathematics, Physics and Computer Science of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University and are open to visitors. The main types of classes – lectures, practical and laboratory classes, meetings with specialists in the field of informatics, teachers of general secondary education, participation in scientific and practical activities. Individual educational and research activities are combined with participation in scientific and practical activities.

The program of work of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" is prepared in advance, all members of the department, as well as members of the STEM center of previous years take part in its formation. The topics of the center's classes are reviewed and updated at the beginning of the school year. The main principles that guide teachers and students in compiling the program are scientific, systematic, as well as personal approach. The high level of scientific knowledge is provided by the highly skilled scientific staff of the department, which has experience, its own traditions and history. Systematization is realized by the clear planning of group meetings, and individuality – in accordance with the content of group meetings to the interests of schoolchildren, students.

In 2019-2021 STEM center worked on the following modern areas of computer science: Python: tkinter library, Windows applications, Construct 2, game creation, Platformer, one-dimensional (multi-dimensional) arrays, modern methods of Web page layout, ways to use graphic images in applications with graphical interface (on Lazarus), Bezier and Hermit problems, practical application of knowledge and skills in mathematics and computer science to solve real problems on the example of Google, cryptography: Caesar cipher, Wiegener and RSA cipher, creating cyclic animation, importing images and audio.

It should be noted that the members of the STEM Center have repeatedly met with leading experts in the field of informatics. Thus, in 2019, an interesting report "Augmented Reality (Microsoft HoloLens)" was made by Matviishen, senior project manager of Delphi Software and demonstrated augmented reality with the latest developments in computer science. There was a meeting with the trainer of Intel "Learning for the Future", "Equal Access to Quality Education", Panasonic's interactive equipment expert, multiple winner and winner of the "Teacher-Innovator" competition, Microsoft trainer, Microsoft expert teacher Poida, who acquainted the members of the STEM center with the use of Microsoft services in educational activities.

In the modern realities of the forced transition to distance learning, members of the STEM center "Educational and Scientific Training Center for Informatics and Computer Mathematics" held a number of online classes in which schoolchildren and students participated. During the classes, the participants were provided with software for performing tasks on the subject of the corresponding class: "Actual trends in IT. Algorithms for solving problems"; "Creating loop animation. Import images and audio"; "Animation of particles"; "Python basics: one-dimensional (multidimensional) arrays" and others.

At the stage of empirical research, a questionnaire was used on the attitude of pupils/students to the main functions that should provide STEM-oriented educational environment to support the implementation of STEM-approach in the educational process.

In order to study scientific and research interests, expectations from classes, and to determine the priority functions of the work of the STEM center, questionnaires and surveys of the participants of the STEM center are systematically conducted.

In order to determine the priority functions that should be provided by the STEM center "Educational and Scientific Training Center for Informatics and Computer Mathematics", we used the online survey method. The online survey was conducted using the Google Form tool. Participants of the STEM center were the respondents of the online survey. Since the respondents were students of a senior specialized school and students of junior courses, the survey was conducted according to one form of the questionnaire. Respondents were asked to rate the functions of the STEM center that we highlighted on a scale of significance (1-5 points) (access to the initial data of the questionnaire: https://u.to/qetDHA).

As a result of the study for data analysis we have fully completed 82 questionnaires.

We used factor analysis to determine the question and structure of respondents' perceptions of the functions to be performed by the STEM laboratory. Factor analysis allows to classify survey data in the form of factors and determine the most significant of them for respondents. In our research the obtained factor structures made it possible to identify the most important functions of the STEM laboratory for the respondents. Interpretation of the results of factor analysis was carried out taking into account the contributions of the variance of functions in total variance factor.

Factor analysis allows you to identify a number of key factors that are the basis of the structure of the survey data. Factor analysis was performed by the principal components analysis and varimax rotation (Varimax Normalized). The optimal number of factors and their statistical significance were tested by Kaiser's test. According to the Kaiser criterion, it is necessary to leave only those factors whose eigenvalues are greater than 1.0; factor load is considered significant if its absolute value is greater than 0.5. To determine the stability of the resulting factors, a single factor must contain at least two components.

The result of the selection of factors indicates that the 3-factor solution is optimal for the study data at a significance level of p smaller than 0.05 (table 2).

Table 2
Factor loads of STEM laboratory functions.

№	Function	Factor		
		I	II	III
1	Ensuring learning mobility of pupils / students	-0.021	0.454	0.138
2	Participation in competitions	**0.789**	0.047	0.112
3	Assistance in conducting STEM research	**0.815**	0.091	-0.092
4	Participation in competitions of student scientific works / MAS	**0.697**	0.031	0.187
5	Development of algorithmic thinking of pupils / students	0.118	0.096	**0.909**
6	Development of creative thinking of pupils / students	0.130	0.224	**0.885**
7	Development of collective cooperation between pupils / students; teachers, professionals and employers	-0.314	**0.801**	0.068
8	Providing a combination of creativity and technical knowledge	0.239	0.201	**0.701**
9	Emphasis on the integration of academic disciplines	0.496	**0.751**	-0.034
10	Writing mathematical creative projects of applied direction	**0.729**	-0.016	0.153

Summarizing the results of factor analysis, we can conclude that the function "Ensuring the mobility of students” does not belong to any factor, which indicates that this function is not significant for respondents in the functioning of STEM center.

The percentage of the total variance of each of the identified factors is determined, the results are shown in table 3.

Table 3
The cumulative variance is explained.

Factor	Eigenvalue	Cumulative Eigenvalue	% Total variance	Cumulative %
I	1.284	6.266	6.266	62.661
II	3.075	3.075	30.753	30.753
III	1.907	4.982	4.982	49.819

From table 3, the first factor explains the 62.661% variance of the functions and includes the following functions:

- “Participation in competitions” (factor load – 0.789);
- “Assistance in conducting STEM-research” (factor load – 0.815);
- “Participation in competitions of student research papers / IAS” (factor load – 0.697);
- “Writing mathematical creative projects of applied direction” (factor load – 0.729).

Summarizing the content of the functions included in the first factor, we can highlight a common feature – all of them to some extent demonstrate the desire of respondents to participate in research and feel in the role of scientists.

The second factor explains 30.753% of the variance and includes the following functions:

- “Development of collective cooperation between pupils / students; teachers, specialists and employers “(factor load – 0.801);
- “Emphasis on the integration of academic disciplines” (factor load – 0.751).

For the functions included in the second factor, we can identify such a common feature – the deepening of cooperation between the parties to the educational process.

The third factor explains 49.819% of the variance and includes the following functions:

- “Development of algorithmic thinking of pupils / students” (factor load – 0.909);
- “Development of creative thinking of pupils / students” (factor load – 0.885);
- “Ensuring a combination of creativity and technical knowledge” (factor load – 0.701).

For the functions of the third factor we can identify such a common feature – the formation of innovative thinking, mastering the tools of a creative approach to solving innovative problems.

Thus, the results of the factor analysis allowed us to identify the structure of the main factors in relation to the functions to be provided by the STEM laboratory. The most important factor is the one that includes functions that demonstrate the respondents’ desire to participate in research. Therefore, in the planning of the work of the STEAM center, considerable attention is paid to the participation of pupils/students in Olympiads, competitions of student scientific works, and the small academy of sciences.

The analysis of the internal consistency of the questionnaire on the main functions to be provided by the STEM laboratory was carried out by determining the correlation between factors and its components (table 4).

The level of correlation between the components varies from very weak to moderate (from 0.27 to 0.47), which indicates a high level of discriminant validity of the questionnaire.

During the research, we studied the expediency and effectiveness of the operation of the STEM center in relation to educational, economic and social indicators.

Table 4
Correlation between the functions of the STEM laboratory.

Functions	№ 1	№ 2	№ 3	№ 4	№ 5	№ 6	№ 7	№ 8	№ 9	№ 10
№1	1.00	0.02	0.18	0.08	0.22	0.09	0.25	0.16	0.06	0.12
№2	0.02	1.00	0.61	0.47	0.12	0.25	-0.21	0.18	0.24	0.43
№3	0.18	0.61	1.00	0.42	0.12	0.00	-0.18	0.20	0.34	0.47
№4	0.08	0.47	0.42	1.00	0.23	0.20	-0.16	0.21	0.29	0.41
№5	0.22	0.12	0.12	0.23	1.00	0.71	0.10	0.14	0.12	0.22
№6	0.09	0.25	0.00	0.20	0.71	1.00	0.18	0.35	0.20	0.21
№7	0.25	-0.21	-0.18	-0.16	0.10	0.18	1.00	0.40	0.22	-0.14
№8	0.16	0.18	0.20	0.21	0.14	0.35	0.40	1.00	0.39	0.15
№9	0.06	0.24	0.34	0.29	0.12	0.20	0.22	0.39	1.00	0.38
№10	0.12	0.43	0.47	0.41	0.22	0.21	-0.14	0.15	0.38	1.00

The effectiveness of the work of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" in terms of educational indicators is evidenced by the achievements of pupils/students in various Olympiads, competitions, and presentations at conferences. Thus, significant success was achieved by students who took part in the II stage of the All-Ukrainian Student Olympiad in Programming (quarter finals of the ACM ICPC World Championship) in the South-West region (2019). The VSPU-BreakOut team, consisting of Dmytro Boichuk, Svitlana Tkachenko, and Yuri Lyulko, took 1st place among the teams of pedagogical educational institutions and 2nd place among the teams of pedagogical educational institutions in the III (final) stage of the All-Ukrainian Student Programming Olympiad, Maria Levytska participated in the All-Ukrainian competition of student scientific works in mathematics and statistics and was awarded a diploma for significant achievements. Participant of the STEM center and student of the senior specialized school Iryna Turzhanska won the first place in the II stage and the III place in the III stage of the All-Ukrainian competition for the defense of research works of students who are members of the Small Academy of Sciences of Ukraine.

Using the method of surveying pupils/students, we have determined the competencies that, in their opinion, contribute to the formation of classes in the STEM center. According to the results of the survey, 96% of respondents chose the competence "development of technical culture", "acquiring experience of own design activity" – 85%, "acquiring experience of inventive activity" – 56%, "acquiring experience of research and experimental activity" – 65%, "development of design abilities" – 86%, "development of logical thinking" – 96%; "development of creative initiative and self-realization" – 98%.

The STEM center is free for pupils/students, so from the point of view of the economic effect, it contributes to the optimization of financial expenses by parents for extracurricular education of children in the direction of STEM.

Among the social indicators related to the functioning of the STEM center, we single out the popularization of STEM education, increasing the prestige of science and mathematics professions.

To contextualize our findings, we conducted a comparative analysis with similar STEM center implementations globally. Table 5 presents key performance indicators across different institutional contexts.

Table 5
Comparative outcomes of STEM centers across different contexts.

Indicator	Our study (Ukraine)	US centers	European centers	Asian centers
Student retention rate	87%	82-91% [79]	79-85% [80]	88-94% [33]
Research participation	62.7%	45-55% [81]	50-60% [32]	65-75% [34]
Underrepresented group engagement	42%	35-48% [82]	38-45% [53]	40-52% [51]
Faculty adoption of innovation	73%	68-75% [83]	70-78% [22]	75-82% [84]

Our findings align closely with international benchmarks, with notably strong performance in student retention and research participation. The high engagement rate in research activities (62.7%) exceeds many comparable programs, suggesting effective implementation of inquiry-based approaches and mentorship structures.

5. Conclusions and recommendations

Introduction of methodical decisions of STEM education in educational process of educational institutions allows to form in pupils, students the most important competences of the modern expert: ability to see and formulate a problem, ability to suggest ways of its solution, flexibility as ability to understand a new point of view and stability in defending the position, originality of ideas, ability to abstract, concretize, analyze and synthesize. The implementation of STEM education approaches presupposes that students learn about technology, field of knowledge and acquire practical skills at the same time. Early involvement of pupils and students in STEM can support not only the development of creative, technical thinking, but also contribute to better socialization of the individual, because it develops such skills as: cooperation, communication, creativity.

Our study demonstrates that modern STEM centers, when properly designed and implemented, serve as transformative educational resources that significantly enhance undergraduate science and mathematics training. The integration of technology-enhanced learning modalities, including 24/7 online support modules and micro-credentialing systems, creates flexible pathways that accommodate diverse learning needs and schedules. This flexibility is particularly crucial in the Ukrainian context, where economic constraints and geographical disparities can limit access to traditional educational resources.

The factor analysis results reveal three critical dimensions that drive STEM center effectiveness: research participation aspirations (62.661% variance), collaborative cooperation (30.753% variance), and innovative thinking development (49.819% variance). These findings align with global evidence suggesting that successful STEM centers must balance cognitive skill development with psychosocial support mechanisms [85, 86]. Particularly noteworthy is the strong emphasis on research participation, which exceeds international benchmarks and suggests effective cultivation of scientific identity among participants.

As a result of the research, we highlighted the key performance indicators of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" at Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University:

- for the university: promotion of STEM education among young people;
- for teachers: mastering modern technologies in demand in the labor market, awakening interest of students in the disciplines of the natural cycle, the disclosure of creative potential of youth, the search for talented youth, talents;
- for students: increasing competitiveness in the labor market through the mastery of modern technologies, participation in competitions, contests, competitions of student research papers;
- for teachers of general secondary education: providing methodological assistance on the implementation of STEM education in the educational process;
- for students of general secondary education institutions: participation in competitions, research contests of the Small Academy of Sciences of Ukraine, adaptation of future entrants to the conditions of student scientific activity; the opportunity to decide on the choice of a future profession, which will influence the choice of a higher education institution for further education and realization of a life trajectory;
- for parents: free participation of students in the projects of the STEM center will allow to optimize financial expenses from the family budget for extracurricular education in the STEM direction.

In the future, the STEM center plans to design and operate a laboratory for educational robotics [87, 88, 89].

It is planned that the main purpose of the laboratory of educational robotics will be:

- information and analytical work on topical issues of robotics in order to provide information to the educational process, strengthening its practical direction;
- use of software to control the electronics and mechanics of robots;
- collection of materials for research and preparation of publications in accordance with the scientific topics of the laboratory;
- 3D modeling and printing of prototypes and ready-made models of robots on a 3D printer;
- analysis of world practices in the field of robotics and information technology;
- organization and participation in scientific, educational and educational activities in the field of robotics.

On the basis of STEM laboratory in the future it is planned to conduct a training course on the organization of project-technological and interdisciplinary project activities, development of methods of STEM training, creation of interactive complexes for lessons, reports, lectures, laboratory and practical classes, presentations for studying natural sciences and mathematics.

The results of the pedagogical research on the perception of responders of the functions performed by the STEM center were analyzed by means of factor analysis. Factor analysis was performed using principal component analysis and varimax rotation (Varimax Normalized). The optimal number of factors and their statistical significance were checked according to the Kaiser criterion.

So, the goal has been achieved, the tasks of the scientific research have been successfully fulfilled, namely:

- the analysis of trends in the development of education in the field of STEM has been carried out based on the practical experience of scientists from different countries;
- the normative and legal field of implementation of the state program of the STEM field in Ukraine was investigated;
- thanks to the experience of the operation of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science of the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, the popularization of STEM education among young people, teachers of general secondary education institutions and teachers has been ensured higher educational institutions;
- the purpose of the operation of the STEM center for junior year students and pupils, teachers of general secondary education institutions, key indicators affecting the development of education in the field of STEM as an innovative direction of the development of science and mathematics education in Ukraine is defined;
- holding meetings in the direction of STEM education with leading specialists in the field of computer science to involve scientific and pedagogical workers in the use of new technologies, as well as their training, retraining or advanced training for the effective use of STEM tools as tools for training and career guidance of pupils/students;
- a questionnaire was conducted, interviewing respondents to study scientific research interests, expectations from classes, determining the priority functions of the STEM center, competences, the formation of which is facilitated by classes, to analyze the structure and perception by respondents of the functions that the STEM center should perform, we used factor analysis;
- determined the prospects for further research.

Based on our findings and global evidence, we propose the following strategic recommendations for institutions seeking to establish or enhance STEM centers (figure 4):

1. *Technology infrastructure*: Invest in robust online platforms that provide 24/7 access to learning resources, virtual laboratories, and collaborative tools. Evidence shows that hybrid models combining online and in-person support achieve optimal outcomes [15, 16].
2. *Professional development*: Implement structured communities of practice and mentorship programs for faculty. Train-the-trainer models and peer learning networks significantly enhance adoption of innovative pedagogies [90, 91].

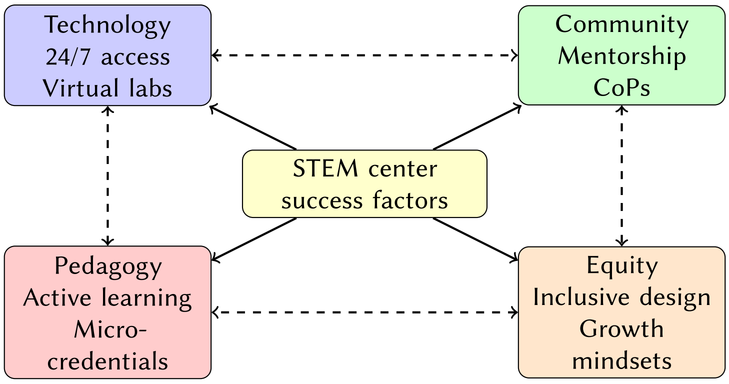

Figure 4: Integrated success factors for modern STEM centers.

3. *Equity-centered design*: Prioritize inclusive curricula and culturally responsive teaching methods. Growth mindset interventions and identity-affirming practices are particularly effective for underrepresented groups [92, 93].
4. *Assessment and continuous improvement*: Develop comprehensive assessment frameworks that capture both cognitive and psychosocial outcomes. Regular evaluation enables evidence-based refinement of programs [77].
5. *Strategic partnerships*: Foster multi-stakeholder collaborations between universities, schools, industry, and community organizations. These partnerships enhance resource availability and real-world relevance [94, 95].

Building on our findings and global trends, we identify several critical areas for future research:

1. Multi-year tracking of student outcomes to assess sustained effects of STEM center interventions on career trajectories and professional development [18].
2. Systematic evaluation of AI-driven personalization [96], augmented reality laboratories [97, 98, 99, 100, 101, 102, 103, 104, 105], and blockchain-enabled credentialing systems in STEM education contexts [13, 106, 107].
3. Deep investigation of how STEM centers can better serve students with multiple marginalized identities, incorporating culturally sustaining pedagogies [108].
4. Development and testing of cost-effective implementation frameworks for resource-constrained institutions, particularly in developing countries [109].
5. International collaborative studies examining how cultural contexts influence STEM center effectiveness and student engagement patterns [110].

These research directions will contribute to the development of more inclusive, effective, and sustainable STEM education models that can address the complex challenges facing 21st-century education systems globally. As Ukraine continues to integrate into the European and global educational space, the experiences and insights from our STEM center implementation can inform similar initiatives in comparable contexts, particularly in countries undergoing educational reform and modernization.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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