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Application of STEM Components in Educational Robotics as a Means of Early Career Guidance to Technical Professions

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Abstract: *The article* ***aims*** *to theoretically justify the use of STEM components in educational robotics as a means of early career guidance for secondary school students toward technical professions. The work uses* ***method****s of systematic analysis, comparative review, and generalization of the results of more than 15 scientific publications (2019–2025) by Ukrainian and foreign authors. A content analysis of meta-studies evaluating the impact of robotics on the academic achievement and motivation of students was carried out, as well as a synthesis of empirical studies devoted to practical formats of robotics classes. The* ***results*** *prove that educational robotics organically combines science, technology, engineering, and mathematics, creating a practice-oriented environment that promotes the formation of STEM competencies. An analysis of meta-studies and review papers shows that robotics classes have a moderately positive impact on students' academic achievements and their attitude toward the educational process. Integrated* *interdisciplinary courses, clubs, and competitive platforms increase interest in technical disciplines and develop project skills, critical thinking, and teamwork. The problem of standardizing didactic approaches and methods for assessing the career guidance effect, as well as adapting international models to the Ukrainian context and resource provision for educational institutions, remains unresolved. The* ***conclusions*** *summarize that the proposed conceptual framework for integrating STEM components into robotics educational projects at the level of general secondary education institutions enables the development of practical recommendations on the structure of classes, forms, and tools for assessing career guidance. The widespread implementation of such a model in the future will contribute to the timely identification of technical aptitudes among students, the formation of a lasting interest in engineering and technical professions, and the improvement of the quality of professional self-determination.*

Keywords: *Educational robotics, STEM education, early career guidance, secondary school, interdisciplinary learning, STEM competencies, career guidance model.*

Застосування STEM-компонентів в освітній робототехніці як засіб ранньої профорієнтації в технічні професії

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Анотація: *Стаття має на* ***меті*** *теоретично обґрунтувати застосування STEM-компонентів в освітній робототехніці як засобу ранньої* *профорієнтації здобувачів закладів загальної середньої освіти до технічних професій. У роботі застосовано* ***методи*** *системного аналізу, порівняльного огляду та узагальнення результатів понад 15 наукових публікацій (2019–2025 рр.) українських і закордонних авторів. Здійснено контент-аналіз метадосліджень, що оцінювали вплив робототехніки на академічні досягнення й мотивацію здобувачів освіти, а також синтез емпіричних досліджень, присвячених практичним форматам занять із робототехніки. У* ***результатах*** *доведено, що освітня робототехніка органічно поєднує науку, технології, інженерію та математику, створюючи практико-орієнтоване середовище, яке сприяє формуванню STEM-компетентностей. Аналіз метадосліджень та оглядових праць засвідчує наявність помірно позитивного впливу занять із робототехніки на навчальні досягнення здобувачів освіти та їхнє ставлення до освітнього процесу. Інтегровані міждисциплінарні курси, гуртки та змагальні платформи підвищують інтерес до технічних дисциплін, розвивають проєктні навички, критичне мислення та командну взаємодію. Нерозв'язаною залишається проблема стандартизації дидактичних підходів і методик оцінювання профорієнтаційного ефекту, а також адаптації міжнародних моделей до українського контексту та ресурсного забезпечення закладів освіти. У* ***висновках*** *підсумовано, що запропонована концептуальна рамка інтеграції STEM-компонентів у робототехнічні навчальні проєкти на рівні закладу загальної середньої освіти уможливлює розробку практичних рекомендацій щодо структури занять, форм та інструментів оцінювання профорієнтації. Масове впровадження такої моделі в майбутньому сприятиме своєчасному виявленню технічних нахилів здобувачів освіти, формуванню стійкого інтересу до інженерно-технічних професій і підвищенню якості професійного самовизначення.*

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Ключові слова*:* *освітня робототехніка, STEM-освіта, рання профорієнтація, заклади загальної середньої освіти, міждисциплінарне навчання, STEM-компетентності, профорієнтаційна модель.*

Problem Statement. In the context of ongoing scientific and technological progress, modern education is focused on preparing young people to meet the demands of the knowledge economy, particularly in relation to STEM careers [1]. The integration of STEM components (Science, Technology, Engineering, and Mathematics) into the educational process represents a key direction in the global modernization of learning systems. One of the most promising tools for implementing the STEM approach is educational robotics, which facilitates interdisciplinary learning through project-based activities involving robotic technologies. In recent years, educational robotics has garnered increasing attention from researchers. This growing interest is evidenced by the rising number of scholarly publications in the field [2].

In Ukraine, the implementation of STEM education and robotics is supported at the state level, including the initiation of nationwide experimental programs and the development of educational curricula in robotics. However, a shortage of qualified professionals in technical fields remains a pressing issue, highlighting the urgent need to promote early career guidance for students toward technical professions. In this context, research into the potential of applying STEM components through educational robotics to foster students' interest in technical specializations is highly relevant.

Despite the growing emphasis on STEM education, the system of career guidance for students in engineering and technical fields remains insufficiently effective [3]. Traditional approaches to vocational training and career counseling do not consistently generate sustained interest among adolescents in engineering and scientific professions [3]. At the same time, educational robotics demonstrates considerable potential to address this issue by combining interdisciplinary learning with hands-on tasks that closely resemble real-world technical projects.

However, the widespread implementation of robotics in educational institutions raises several debated concerns. An analysis of both domestic and international experience reveals that the application of educational robotics is often fragmented and lacks systematic integration. In most cases, it is limited to extracurricular clubs or individual initiatives rather than being a required component of formal educational programs. In Ukraine, there is a notable shortage of scientific and pedagogical studies that examine the didactic potential of educational robotics and its impact on preparing students for STEM-related careers [3].

Analysis of Recent Studies and Publications. A review of scientific literature highlights the multifaceted approaches to implementing educational robotics, which are reflected in various directions and focal points of research in this field. For instance, Yu. Matviienko [1] examined the didactic potential of sports-oriented educational robotics and emphasized the role of competitive elements in developing key 21st-century competencies. O. Strutynska [2] assessed the relevance of introducing robotics in Ukrainian schools, stressing the need to adapt international programs to the national educational context. The importance of designing well-structured case-based lessons for the effective integration of STEM tools into primary education was underscored by O. Shkurenko and Ye. Lobyriieva [3]. The main directions of research in educational robotics were identified by S. Anwar et al. [4], outlining both challenges and prospects. The significant impact of extracurricular robotics clubs on students' interest in STEM fields was confirmed in the study by O. Ayeni et al. [5]. The importance of applying mastery learning theory to develop step-by-step project modules in robotics was substantiated by C. Chang and Y. Chen [6]. The appropriateness of integrating robotics courses into primary

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school education, fostering positive attitudes towards STEM, was demonstrated by Y. Ching et al. [7]. Contemporary trends in robotics-based STEM education based on a technology-oriented learning model were described by D. Darmawansah et al. [8]. A three-stage program that significantly enhances older students' interest in STEM careers was proposed by İ. Dökme and Z. Hancıoğlu [9]. The optimization of digital tools in professional training was explored by D. Drofa [10], while K. Ivanchenko [11] examined the role of adaptive learning in the training of automation engineers. Researchers F. Ouyang and W. Xu [12] confirmed the moderate positive effect of robotics on academic outcomes; G. Ragusa and L. Leung [13] demonstrated its impact on students' interest in IT careers; and J. Sáez-López et al. [14] highlighted its contribution to deeper mathematical and scientific understanding through the use of mBot. O. Strutynska and S. Baranov [15] outlined trends in extracurricular robotics education; I. Torres and E. Inga [16] emphasized its influence on teenagers' cognitive skill development; and I. Trapero-González et al. [17] systematized data on the development of STEM competences in primary education through robotics.

Identification of Previously Unresolved Aspects of the General Problem. Despite the broad scope of research on educational robotics within STEM education, there is still no generalized methodology for integrating STEM components into courses aimed at career guidance for students in secondary education institutions. Standardized tools for assessing the impact of robotics-based projects on students' career intentions have yet to be developed. Furthermore, the specific features of adapting international approaches to the context of Ukrainian secondary schools and the requirements for resource provision remain insufficiently studied. This research aims to address these gaps by developing a conceptual framework and practical solutions that can be used to effectively integrate robotics into career-oriented STEM courses at the secondary school level.

 ISSN: 2786-9458

Research Objective. The objective of this study is to theoretically substantiate the potential of applying STEM components in educational robotics as a tool for early career guidance of students in general secondary education institutions toward technical professions.

To achieve this objective, the following tasks have been define:

1) to analyze current scholarly approaches to the implementation of STEM education and robotics in secondary schools;

2) to justify pedagogical conditions and approaches for using robotics as a tool for guiding students toward careers in technical fields;

3) to formulate recommendations for integrating STEM components (scientific knowledge, technology, engineering design, mathematics) into robotics-based learning projects to enhance their career-guidance potential.

Presentation of the Main Research Material. Educational robotics integrates knowledge from various academic disciplines within a single, practice-oriented learning environment. This enables students to simultaneously master the fundamental principles of natural sciences, engage with modern technological tools, develop engineering skills, and strengthen their mathematical abilities. Through this approach, students not only study theoretical concepts but also apply them in practice, which significantly enhances both comprehension and motivation for learning.

Each robotics project involves working with complex physical laws. Students learn to accurately configure and calibrate sensors for measuring temperature, light intensity, or distance, analyze the data obtained, and draw conclusions about the operation of the devices. At the same time, they conduct numerous experiments with software by developing control algorithms, debugging code in languages such as Python or C++, testing various logical structures, and learning to identify and correct errors in their programs.

 ISSN: 2786-9458

A separate stage involves the construction of the hardware component: learners design the chassis, develop motion mechanisms, build the robot's frame, and select appropriate materials and tools, which allows them to acquire hands-on technical skills. They also apply mathematical modeling by calculating motion trajectories, optimizing system parameters, and determining angles and velocities. This process provides a clear understanding of the role of mathematics in engineering.

This interdisciplinary approach promotes deep comprehension, as learners recognize how abstract theorems from school-level physics and mathematical formulas are implemented during the design, assembly, and configuration of robots, progressing from theoretical problem formulation to the practical realization of a functional device [1, p. 53].

The implementation of interdisciplinary robotics courses has demonstrated the high effectiveness of this educational model. Specifically, C. Chang and Y. Chen developed a course in which learners designed an Arduino-controlled sailboat, integrating lessons from physics (analyzing wind force and thrust, modeling sail behavior), computer science (writing and optimizing code to control the motor and process sensor data), and engineering design (constructing the hull, selecting materials, calculating strength, and ensuring water resistance) into a single STEM module [6, p. 624]. In each phase, including planning, prototyping, and testing, students worked in small teams. They developed skills in project management, task delegation, and collaborative problem-solving. This step-by-step approach enabled them not only to master each conceptual block individually but also to understand their interconnections. They learned to analyze how changes in the code affected the sailboat's movement, assess the efficiency of different hull designs, and adjust mathematical models to improve navigational accuracy.

An analysis of Ukrainian pedagogical practices confirms that educational robotics facilitates and enhances the development of 21st-century competencies. It fosters critical thinking, the ability to solve complex problems, creativity, and teamwork skills [1, p. 53]. The high level of learner motivation in such courses can be attributed to the opportunity to observe tangible results of their work, such as a functioning robot powered by their programming and engineering efforts. It is also driven by the chance to present their solutions to peers and instructors.

Given this context, the integration of robotics activities into core curricula allows educational goals to be simultaneously achieved across four disciplinary domains. Learners apply physical laws, algorithmic thinking, engineering approaches, and mathematical calculations within a single project. This format enhances the motivational effect, which is essential for deep learning, as it combines theory with practice and demonstrates the real-world relevance of STEM competencies.

A meta-analysis of numerous experimental studies has shown that incorporating robotics into the educational process has a moderate positive effect on learners' academic performance, attitudes toward learning, and motivation to engage with complex subjects [11]. In particular, in primary school settings, integrated robotics modules consisting of 10 to 12 lessons in programming and configuring simple mechanisms not only increased children's interest in science and technology subjects but also transformed their overall perception of learning. Many students began to view difficult topics as engaging challenges and creative experiments rather than dry memorization of facts [7]. According to surveys conducted before and after the course, over 70 percent of learners reported increased confidence in their abilities and a greater willingness to engage with technical tasks. Moreover, the average scores on mathematics and physics assessments rose by 10 to 15 percent.

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In middle school, similar robotics programming courses delivered within computer science lessons contributed to the development of essential cognitive skills, including logical reasoning, spatial visualization, and both analytical and synthetic approaches to problem-solving [15, p. 197]. Learners practiced algorithmic thinking by designing robot movement through mazes while simultaneously learning to analyze experimental outcomes and draw conclusions based on collected data. In addition, completing team-based tasks improved their communication abilities and fostered collaboration during the joint design and testing of devices.

Ukrainian educators report that regular robotics classes cultivate a sustained interest in technical creativity and engineering thinking among learners and significantly enhance their readiness to pursue a STEM-oriented educational path in the future [3, p. 123]. They note that students not only absorb course material more effectively but also actively propose original ideas for improving designs, demonstrate ingenuity in non-standard situations, and develop the ability to critically evaluate their work. These shifts in attitudes and learning strategies lay a foundation for future professional self-determination and personal development in technical fields.

Furthermore, practice shows that robotics activities lead to a noticeable improvement in learners' performance across other subject areas as well, significantly expanding the boundaries of the traditional educational process. For example, integrated mathematics lessons involving mBot robots include not only solving equations and graphing functions on paper but also applying these skills in project-based tasks. Learners calculate robot trajectories using formulas, program the device to follow predetermined routes, and configure sensors to monitor the accuracy of movement. This promotes a deeper understanding of abstract mathematical and scientific concepts [13].

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During such lessons, learners experience the interconnectedness of science and mathematics, as geometric constructions and algebraic calculations have a direct impact on the robot's behavior in space.

At the same time, robotics serves as a tool for developing both practical and analytical skills, as learners are trained to align theoretical models with real experimental data, analyze deviations from expected results, and adjust their calculations or code accordingly. This fosters critical thinking and the ability to tackle complex tasks. Thus, educational robotics fulfills two core functions. First, it integrates knowledge from various disciplines into a single practice-oriented environment where each mathematical formula or scientific principle finds tangible expression in the operation of a mechanism. Second, it makes learning more engaging, hands-on, and meaningful for students, which enhances their active participation and builds lasting motivation to study technical subjects.

This practice lays the groundwork for learners' future professional self-determination and informed selection of technical fields. Examples of STEM component integration are presented in Table 1.

Table 1

Examples of STEM Component Integration in Educational Robotics and Their Career Guidance Impact on Secondary School Learners

STEM Component	Example of Robotics Activity	Core Skills Acquired	Career Guidance Impact
Science	Experiments using sensors (e.g., temperature measurement)	Understanding of physical principles	Interest in the field of physical engineering
Technology	Programming Arduino to control LED lights	Fundamentals of coding	Motivation to pursue IT-related professions

 ISSN: 2786-9458

Engineering	Designing the chassis of a mobile robot	Mechanical design skills	Engagement with engineering-related specialties
Mathematics	Solving algorithmic routing tasks	Logical and critical thinking	Awareness of the role of mathematics in technology

Source: compiled by the author based on [5; 6]

One of the main objectives of implementing STEM education is not only to provide learners with basic knowledge in science, technology, engineering, and mathematics but also to help them form a clear understanding of their future professional trajectory in these fields [8, p. 12]. In this context, educational robotics serves as a unique tool that simulates real engineering and technical processes in an accessible school environment.

During lessons, learners act as programmers by configuring controllers, writing and debugging high-level code that sends commands to robots, and analyzing sensor data to assess the accuracy of algorithms [7, p. 591]. As designers, they develop and construct chassis, lever mechanisms, and structural components using 3D modeling and basic hand tools for material processing. At the same time, they study the physical principles of sensor and actuator operation, such as electromagnetic induction and distance measurement using ultrasonic sensors. They also apply mathematical models to calculate motion trajectories, optimize speed, and adjust turning angles [13].

Each instructional session consists of several stages. It begins with group development of the technical task and assessment of available resources, followed by prototype construction and electronic component integration. Next, learners proceed with software configuration and real-world testing. After testing, they analyze the results, record observations in project journals, and present the working

 ISSN: 2786-9458

prototype to the team while discussing potential improvements. This comprehensive format cultivates systems thinking, the ability to view the project as an integrated whole, as well as project management skills such as planning work phases and distributing responsibilities. It also strengthens learners' ability to collaborate effectively and communicate their ideas clearly.

Starting from primary school, robotics clubs foster a sustained and positive attitude toward STEM. According to several surveys, more than 80 percent of learners who participated in such clubs reported increased interest in pursuing careers in technology-related fields and had well-defined expectations regarding their development in these areas [7; 13]. These clubs typically meet twice a week for 90-minute sessions. Learners work in small teams on their own projects, receive feedback from instructors, and present their results at school STEM fairs. It is through these hands-on activities that children develop cognitive problem-solving skills, learn to adapt existing solutions, and generate their own innovative ideas.

In secondary school, integrated courses that combine physics, mathematics, and computer science through complex robotics programming tasks enhance both learners' academic motivation and overall performance. According to research, after completing a 12-week robotics module, students' scores on physics and mathematics assessments increased by an average of 25 percent, while their understanding of fundamental scientific concepts significantly deepened and became more firmly established [15].

Such courses typically follow several stages. Initially, the instructor and learners jointly formulate the problem to be solved. Learners then work in small groups to develop ideas and create a technical project specification. Following this, teams construct prototypes, connect sensors and teaching controllers, program the robots' behavior, and test the systems under real conditions. In the final phase,

 ISSN: 2786-9458

learners analyze the results, discuss unexpected errors, and propose ways to optimize both the algorithms and the mechanical design.

Each of these phases simulates a genuine engineering cycle, from concept to final product, and helps learners develop project management skills, critical thinking abilities, and effective team collaboration.

Extracurricular robotics clubs and national competitions, such as the FIRST LEGO League and RoboCup Junior, offer learners the opportunity to immerse themselves in an environment of innovation and real team-based challenges, significantly enhancing their career readiness [5, p. 362]. Within these clubs, learners are able to collaborate with engineer-mentors, engage in more complex projects, and participate in demonstrations and public presentations of their developments. According to a comprehensive analysis, more than 75 percent of club graduates chose specialized STEM tracks in upper secondary school and continued their studies in technical fields at higher education institutions, compared to only 30 percent among their peers [12].

At the same time, ensuring a sustainable career guidance effect requires equal access to such programs. It is essential to eliminate geographic, financial, and social barriers and to integrate extracurricular activities with the formal school curriculum to maintain learner motivation throughout the entire educational trajectory [16]. As a result of combining work on real projects, mentorship by practicing engineers, and a healthy competitive atmosphere, learners develop a clear understanding of attainable career paths in technical fields and gain greater self-confidence.

Table 2 presents a comprehensive comparison of possible formats of educational robotics activities and outlines their key advantages from the perspective of career orientation.

Table 2

Formats of Robotics Activities and Their Career Guidance Impact

Activity Format	Description	Core STEM Aspects	Career Guidance Benefits	Potential Limitations
Construction Lesson	Classroom-based session where learners assemble a robot using provided instructions	Engineering, Technology	Introduction to the design process, development of technical skills	Fixed scenario with limited room for creativity
Project-Based Module	Multi-session course focused on designing and building a custom robot	Science, Mathematics, Technology	Development of interdisciplinary thinking and learner autonomy	Requires extended time and access to materials and resources
Club or Workshop	Extracurricular activity involving competitions and collaborative projects	All four STEM components	Motivation through competition, teamwork experience	May be inaccessible to some learners due to time or financial barriers
Inter-School Competition	Team-based challenge involving complex technical tasks	Engineering, Technology, Science	Networking with peers, exposure to professional engineers	Competitive atmosphere may discourage less confident participants
Online Module	Virtual simulations and robot programming tasks	Technology, Mathematics	Accessibility, task adaptability	Limited opportunities for hands-on construction and assembly

Source: compiled by the author based on materials from [12; 13].

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At the national level, educational robotics plays a vital role in laying the foundation for training future engineers within the general secondary education system. As noted by O. V. Shkurenko and Ye. O. Lobyriieva, the groundwork for developing qualified STEM professionals is established at the primary and lower secondary school levels through the active implementation of STEM education [3, p. 123]. Our study confirms that robotics clubs and classroom-based activities at the secondary school level serve as effective mechanisms for early career orientation, allowing students to identify and develop their technical aptitudes. Already in adolescence, learners who are engaged in robotics tend to make more informed decisions about their academic specialization, such as choosing a physics and mathematics track or an engineering-focused program [9].

Thus, the integration of STEM components into educational robotics promotes sustained interest in technical professions by enabling students to gain hands-on experience and solve real-world technical problems. This becomes a key factor in building an effective educational trajectory and in cultivating human capital for high-tech industries.

Conclusions. The analysis of STEM implementation approaches confirms that educational robotics programs in secondary schools exhibit several common trends: interdisciplinary integration of physics, computer science, and engineering; a step-by-step approach to developing algorithmic thinking; and a significant increase in learners' academic motivation and performance. Most scholars emphasize that engagement in hands-on projects fosters students' systems thinking regarding engineering processes and enhances their awareness of potential future careers in STEM fields.

The pedagogical conditions for the effective use of robotics have been substantiated. These include the availability of modern technical infrastructure, a

ISSN: 2786-9458

clearly structured step-by-step curriculum, and teacher readiness to facilitate team-based project activities. Equally important are the organization of a learning environment that enables rapid prototyping, the use of digital simulators, and the provision of mentorship support from practicing engineers.

Practical recommendations have been developed for integrating STEM components into robotics activities. These recommendations include the combination of scientific experimentation, programming, mechanical design, and mathematical modeling. It is proposed to incorporate project-based modules with real-world technical tasks, competitive elements to stimulate motivation, and reflection phases involving discussion of outcomes, all of which contribute to the formation of professional intentions.

The prospects for further research involve testing the proposed framework in various educational contexts, developing standardized tools for evaluating career orientation impact, and exploring the sociocultural factors that influence the choice of technical professions. It is also advisable to conduct long-term monitoring of learners to assess the sustainability of their career intentions and to develop online platforms to support extracurricular robotics activities.

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