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STEM education: the core methodological approaches

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Abstract. The article presents a comprehensive analysis of methodological approaches underpinning the development and implementation of STEM education. The relevance of the study is determined by the need for a holistic methodological substantiation of STEM education, which over the past two decades has acquired a multidimensional and interdisciplinary character in both domestic and international pedagogical science. It is established that the systemic approach is of fundamental importance for overcoming subject fragmentation and fostering systemic thinking, which is essential for addressing complex global challenges of the 21st century. The learner-centred approach emphasizes the unique abilities, interests, and cognitive profiles of learners, ensuring individualization and differentiation of the educational process. The activity-based approach substantiates knowledge construction through active engagement, correlating with L. Vygotsky’s concept of the “zone of proximal development” and J. Dewey’s ideas of experiential learning. The project-oriented approach ensures the authenticity of the educational process by integrating all components of STEM and orienting

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learning toward the creation of real or realistically achievable products. The contextual approach provides knowledge with practical meaning by linking it to socio-cultural and technological challenges, including issues of technological sovereignty, ecological security, and innovative development. The inquiry-driven approach models the activities of scientists and engineers, fostering learners' skills in critical thinking, dealing with uncertainty, and conducting scientific experiments. In summary, the systemic, learner-centred, activity-based, project-oriented, contextual, and inquiry-driven approaches together form an integrated and complementary methodological framework for STEM education. Their combination enhances the effectiveness of the educational process, promotes the development of scientific literacy and engineering thinking, and prepares specialists capable of responding to contemporary scientific, technological, and societal challenges. Prospects for further research are identified.

Keywords: STEM education, systemic approach, learner-centred approach, activity-based approach, project-oriented approach, contextual approach, inquiry-driven approach, methodological framework.

STEM-освіта: основні методологічні підходи

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Анотація. У статті здійснено комплексний аналіз методологічних підходів, що лежать в основі розвитку та реалізації STEM-освіти. Актуальність дослідження зумовлена потребою у цілісному методологічному обґрунтуванні STEM-освіти, яка протягом останніх двох десятиліть набула багатовимірного та міждисциплінарного характеру у вітчизняній і зарубіжній педагогічній науці. Визначено, що системний підхід

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має фундаментальне значення для подолання предметної фрагментарності та формування системного мислення, необхідного для розв'язання складних глобальних проблем XXI століття. Особистісно орієнтований підхід акцентує увагу на унікальних здібностях, інтересах і когнітивних профілях здобувачів освіти, забезпечуючи індивідуалізацію та диференціацію навчання. Діяльнісний підхід обґрунтовує конструювання знань через активну діяльність, що співвідноситься з концепцією «зони найближчого розвитку» Л. Виготського та ідеями досвідного навчання Дж. Дьюї. Проєктний підхід забезпечує автентичність освітнього процесу, інтегруючи всі компоненти STEM та орієнтуючи навчання на створення реального або наближеного до реального продукту. Контекстний підхід надає знанням практичного сенсу, пов'язуючи їх із соціокультурними та технологічними викликами, зокрема проблемами технологічного суверенітету, екологічної безпеки та інноваційного розвитку. Дослідницький (науково-пошуковий) підхід моделює діяльність науковців та інженерів, формуючи в учнів навички критичного мислення, роботи з невизначеністю та проведення наукових експериментів. Узагальнено, що системний, особистісно орієнтований, діяльнісний, проєктний, контекстний та дослідницький підходи утворюють інтегровану та взаємодоповнювальну методологічну систему STEM-освіти. Їх поєднання забезпечує ефективність освітнього процесу, сприяє розвитку наукової грамотності, інженерного мислення та підготовці фахівців, здатних відповідати на сучасні наукові, технологічні й суспільні виклики. Визначено перспективи подальших наукових досліджень.

Ключові слова: STEM-освіта, системний підхід, особистісно орієнтований підхід, діяльнісний підхід, проєктний підхід, контекстний підхід, науково-пошуковий підхід, методологічна система.

Introduction

Topicality of the problem. The topicality of this study is determined by the growing demand for methodological substantiation of STEM education in contemporary pedagogical science. Over the past two decades, STEM has evolved into a multidimensional and interdisciplinary field, actively researched both in Ukraine and internationally. However, despite the proliferation of studies, the issue of a holistic and complementary system of methodological approaches remains insufficiently addressed.

The systemic approach is crucial for overcoming subject fragmentation and fostering systemic thinking, which is indispensable for tackling complex global challenges of the 21st century. The learner-centred approach responds to the societal shift toward valuing personal qualities and self-efficacy as predictors of success, ensuring inclusivity and differentiation in STEM learning. The activity-based and project-oriented approaches provide authentic learning experiences, aligning education with real scientific and engineering practices, while simultaneously cultivating collaboration, creativity, and innovation. The contextual approach situates STEM knowledge within socio-cultural and technological realities, making learning meaningful and practice-oriented. Finally, the inquiry-driven approach models the essence of scientific and engineering activity, equipping learners with research skills and critical thinking necessary for navigating uncertainty.

This study addresses the lack of integrated methodological justification for STEM education, offering a framework that unites systemic, learner-centred, activity-based, project-oriented, contextual, and inquiry-driven approaches. This framework not only enhances the effectiveness of the educational process but also ensures the preparation of specialists capable of responding to contemporary scientific, technological, and societal challenges.

Literature review. The analysis of the scholarly contributions on methodological approaches in STEM education demonstrates the multidimensional and interdisciplinary

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nature of the field, as well as its dynamic development over the past two decades in both domestic and international pedagogical science.

Theoretical conceptualisation of STEM education as an integrated phenomenon is presented in a number of domestic publications. S. Hrytsai and S. Koda summarise the conceptual foundations of integrated learning in natural sciences, mathematics, and technology [5]. N. Balyk and H. Shmyher examine STEM education in the context of teacher training, viewing it as a strategic direction for the modernisation of pedagogical education [3]. Other researchers expand the scope of inquiry by focusing on STEM education as a means of developing scientific literacy and engineering thinking in mathematics lessons [2], and by analysing pathways for preparing future primary school teachers to implement STEM education, evidence of the widening age and level range of the phenomenon under investigation in contemporary scholarly literature [7].

In contemporary pedagogical science, particular attention is devoted to methodological approaches applied in the educational process to ensure its effectiveness and the achievement of expected learning outcomes. Considering the theoretical foundations on which the development and implementation of STEM education are based, the need to substantiate the relevant methodological approaches becomes evident. Among the core methodological approaches we include the systemic, learner-centred, activity-based, project-oriented, contextual, and inquiry-driven approaches [2; 3; 5; 7].

The aim of the article. The aim of the article is to substantiate a set of methodological approaches that underpin the development and implementation of STEM education.

Research results

Within the framework of our study, emphasis should be placed on the systemic approach, which is regarded by contemporary scholars as one of the fundamental approaches in education. As researchers note, "the methodological specificity of the systemic approach lies in the fact that the aim of research is to study the regularities and mechanisms of forming a complex object from certain components. Particular attention is paid to the diversity of internal and external connections of the system, to the process (procedure) of integrating basic concepts into a unified theoretical framework, which makes it possible to reveal the essence of the system's integrity" [9, pp. 9–10]. Its application allows education in general and the educational process in particular to be considered as a holistic, open, dynamic system characterized by a set of components (the triune goal: educational, formative, developmental; a complex of tasks; learning content; corresponding teaching methods and technologies; learning tools; conditions), each of which occupies a specific place in the system, is complementary, and has clear functions and interconnections with other components. "The functional model of the pedagogical system is viewed in terms of organisation, planning, adjustment, dynamism, flexibility, and the operational provision of all possible conditions for readiness to implement its anticipatory function" [1, p. 11].

It is accentuated: "Each component (substructure) within the system most often consists of separate elements. The set and interrelation of these elements determine the role the component will play in achieving the planned result. Thus, if a teacher correctly formulates the educational goal but fails to select appropriate learning material, then regardless of the teaching methods and forms of cognitive activity organization employed, achieving a high positive result becomes impossible. Other violations occur when inadequate methods and forms of organization are chosen for a specific task and content. In such cases, the given educational moment within the system of other moments of the lesson cannot fulfill its intended role, and the actual result of the lesson will be insignificant. Therefore, the level of system integrity depends on its goal orientation, the completeness of its components, the

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quality of each component, and the density of interconnections both among components and between each of them as a whole" [1, p. 13].

For STEM education, the systemic approach is of particular importance, as it enables overcoming traditional subject fragmentation and fosters in learners a holistic, "ecosystemic" perception of scientific knowledge. It cultivates systemic thinking, which incorporates system identification (the ability to distinguish relevant components and connections), the prognostic function (understanding system dynamics), and the design function (the ability to consciously modify the system to achieve desired results). The development of systemic thinking is especially relevant at the beginning of the 21st century, characterised by the complexity of global problems that cannot be solved without the application of the systemic approach. These include scientific and technological challenges that lack simple, single-factor solutions and require an understanding of complex causal relationships, feedback loops, and nonlinear interactions. Accordingly, STEM education that does not foster systemic thinking essentially prepares specialists to solve the problems of the past rather than those of the future.

The practice of the systemic approach in STEM education involves the use of methods for modelling complex systems (ecosystems, climate models, markets), data analysis and synthesis, feedback in laboratory research, as well as the study of systemic archetypes (typical patterns of complex system behaviour). Tools such as system dynamics, agent-based modelling, and complex network analysis are increasingly integrated into STEM curricula at various levels of education: from secondary school to university studies.

With regard to the learner-centred approach, which is viewed from the perspective of humanistic pedagogy and anthropocentrism, the primary focus in education is placed on the learner, their unique abilities, preferences, interests, needs, and learning styles. Accordingly, individualisation of the educational process becomes essential, grounded in the differentiation of content (learning material), process (methods, technologies, conditions), and product (learning outcomes). The relevance of the learner-centred approach is evidenced in scholarly publications emphasising that "today, a society in which knowledge is capital and personal qualities are the key factor of successful life activity sets new tasks for the education system. Therefore, the transition from a cognitively oriented to a learner-centred educational paradigm, based on the ethics of mutual understanding, mutual respect, and creative cooperation, which is observed at the current stage of higher education development in Ukraine, is a natural process" [14, p. 394].

Scholars substantiate their position by identifying the main principles of the learner-centred approach, among which they highlight: "1) personality as a pedagogical category reflects a specific sphere of education and human development and, in this sense, represents its specific goal; 2) just as a person in the educational process masters the experience of applying knowledge, solving cognitive and practical tasks, and developing creative skills, they must also master the ability 'to be a personality,' i.e., to perform specific personal functions (selectivity, reflection, self-realization, self-regulation, social responsibility, etc.)" [14, p. 398].

The application of the learner-centred approach in STEM education presupposes differentiation of the educational process with consideration of learners' cognitive profiles, gender and sociocultural equality, and accessibility of STEM knowledge for all categories of learners. Scholarly publications emphasize that "the system of learner-centred education has the following characteristic features: learner-centred educational content (orientation toward a complex of value orientations: universal, national, regional, group, ethnic, individual); a cultural, integrative, and life-sustaining character of the learning process; a corresponding model of the educational process; a technology for implementing learner-centred education (forms, methods, means of learning); a favourable educational environment as a condition for organizing a learner-oriented process; and the identification of such criteria for assessing education quality that reveal not only the level of learners' competencies but also the

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development of their creative potential under conditions of stable positive motivation for learning and teachers' professional activity" [15, p. 120].

The application of the learner-centred approach in STEM education is directly connected with the concept of self-efficacy, understood as learners' belief and confidence in their ability to overcome obstacles and achieve expected results. It serves as a predictor of success in active exploration of the surrounding world. From the perspective of STEM education, the learning process is designed to create conditions in which learners gradually complete tasks ranging from the simplest to the most complex, thereby fostering confidence in their own abilities and skills. The implementation of the learner-centred approach in STEM education substantiates the use of modern pedagogical tools, including granting learners the right to choose project topics, employing diverse forms of assessment, initiating and implementing mentoring programs, and applying adaptive pedagogical technologies that adjust task complexity and learning pace to the individual needs of each participant.

Alongside the learner-centred approach, an important role is also assigned to the activity-based approach in STEM education. We concur with the view that activity should be regarded "…as a means of personal development and as conscious human engagement manifested in a system of actions aimed at achieving a set goal. Activity represents a mode of human and societal existence, defining an active attitude toward the world, directed at its cognition and purposeful transformation" [10, p. 28]. The author further postulates that "the activity-based approach proceeds from the notion of the unity of personality and activity. This unity is manifested in the fact that activity in its various forms directly or indirectly brings about changes in the structure of personality; while personality, in turn, simultaneously directly and indirectly makes choices of adequate types and forms of activity and transforms activity in ways that meet the needs of personal development" [10, p. 29].

According to the activity-based approach, the acquisition of knowledge cannot be reduced to passive perception of information; it requires purposeful activity on the part of the learner, during which their system of knowledge is constructed. This construction occurs in the course of learning activity, where a dissonance arises between existing knowledge and the unknown, between what the learner can accomplish independently and what requires the assistance of a teacher or collegial collaboration. Such an interpretation of the essence of the activity-based approach is reflected in the works of Vygotsky, who argued for the "zone of proximal development" as a key prerequisite for further growth [17].

Domestic researchers interpret the essence of the activity-based approach through the proposition that "…the psyche of the individual is inseparably connected with their activity and conditioned by it. Activity is understood as conscious human engagement manifested in the process of interaction with the surrounding environment, and this interaction consists in solving vital tasks that determine human existence and development" [11, p. 86]. It is noted that "in practice its essence lies in the personalization of pedagogical interaction, which presupposes the rejection of role masks, the adequate inclusion of personal experience (feelings, emotions, actions, and behaviours) of future specialists. The priority of the individual does not diminish the role of the teacher; rather, it makes their task more complex, raising demands on them as organizers of the educational process. The implementation of this approach requires shifting students to the position of subjects of cognition, cooperation, and communication, based on the pedagogical technique of 'equality between teacher and students'" [12, p. 155].

Furthermore, the activity-based approach is considered from the perspective of pedagogical methodology and is defined as one of the approaches employed by educators to improve the educational process through the development and application of new teaching methods: "the activity-based approach in the modern education system provides the foundation for creating new teaching methods, such as the project method, and entire educational systems, such as STEM education, which combines action-oriented learning and

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project-based activity with integrated content from different fields of knowledge. The project-oriented approach is more universal and can be applied in lessons across various subjects, since the product of a project is a tangible and measurable result: a new object, a new technological process, new solutions in social life, or new knowledge, skills, and competencies" [6, pp. 91–92].

In the context of STEM education, organising the educational process on the basis of the activity-based approach involves the gradual complication of tasks, with the possibility of providing support at the level of complexity that represents the "next step" in the learner's development. In this case, forms of organisation such as mentorship of novices by experienced learners, pair programming in computer science, and collaborative laboratory research are employed.

Within the framework of the activity-based approach and its application in STEM education, emphasis should be placed on experiential learning. According to Dewey, activity must be purposeful, reflective, and connected to real questions and problems [16]. Only under these conditions does it become a source of genuine knowledge. This principle substantiates the qualitative difference between algorithmic task execution and authentic research laboratory work, where learners independently plan and interpret both the course of the experiment and the data obtained.

Closely related to the activity-based approach is the project-oriented approach, which at the beginning of the 21st century became one of the most operationalised and research-grounded approaches underpinning STEM education. It is argued that "…project-based activity is one of the dimensions of the cultural level of society, and project work ensures the active involvement of students, teachers, and administrators of vocational education institutions in solving their own life and professional tasks. Some Western scholars even claim that the entire modern world (and not only the education system) can be viewed as a collection of diverse projects. A special term has even emerged – "project-based world" – a world built upon project activity" [13, p. 9].

Unlike the activity-based approach, which emphasises the value of any purposeful activity, the project-oriented approach presupposes the structuring and organisation of learning around a specific, extended project whose outcome is a real or realistically achievable product. This approach naturally integrates all four components of STEM: learners apply scientific knowledge (Science), technological tools (Technology), engineering design methods (Engineering), and mathematical apparatus (Mathematics) within a comprehensive educational process.

Defining the essence of the project-oriented approach, I. Konovalchuk notes that "the fundamental premise in constructing the process of implementing innovations is the recognition that innovation, as a unique, newly created object, cannot be realised through traditional means. Projecting is a technology that enables the development of new, adequate forms and methods of organising innovations in general education institutions. The result of projecting is an innovative project – a system of scientifically grounded concepts, goals, and measures necessary for implementing innovations under the real conditions of a specific educational institution. The project ensures the organisation of the activities of the subjects of the innovation process in space and time" [8, p. 121].

For our study, the rationale for the project-oriented approach is crucial for several reasons that are foundational to STEM education. First, it ensures authenticity, i.e., the alignment of STEM education with real scientific and engineering practices. Second, its orientation toward educational objectives distinguishes it from "projects for the sake of projects" and requires appropriate technological support. In addition, the application of the project-oriented approach in STEM education presupposes a clear problem statement that demands thorough investigation and subsequent design of its solution, while being formulated in a manner accessible to learners. We concur with researchers who argue that the project-

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oriented approach is "...not merely the implementation of educational content, which is artificial and reduces students' motivation to engage in activity. The project-oriented approach is genuine project activity, grounded in a scientific basis, whose results are introduced into various spheres of society – real production, business, science, and the social domain. This significantly enhances the motivation for learning, fosters the self-development of abilities and talents among children and youth, and guides them toward choosing a future profession" [4, p. 10].

Thus, the application of the project-oriented approach in STEM education provides opportunities for integrating theoretical knowledge, practical skills, and competencies in order to accomplish a specific, practically significant task. The execution of this task is realised in the form of a project with a clearly defined goal and objectives, an implementation algorithm encompassing sequential stages, and an outlined expected outcome. This format enables students to apply theoretical knowledge from mathematics, natural sciences, technology, and engineering in real or near-real conditions, thereby increasing motivation and fostering a deeper understanding of the learning material.

With regard to the contextual approach, it should be noted that its foundation lies in enhancing the mastery of knowledge, skills, and competencies, which is realised within a corresponding socio-cultural, educational, and physical context. In STEM education, the contextual approach is particularly significant, since scientific and technical knowledge often appears to students as abstract and devoid of practical meaning.

Characterising contextual learning, scholars argue: "By its very idea it is close to developmental and problem-based learning, which consists in activating students' learning activity. However, contextual learning focuses on the acquisition of knowledge and social experience in the process of active practical activity of the learner. Such a paradigm is promising for vocational education. In secondary education, its possibilities are considerably limited, since, first, students lack sufficient life and activity experience, and second, the fundamental level of knowledge is difficult to transform into practical activity. In the system of non-formal education, which is closer to practice, these possibilities are enhanced" [4, p. 7].

In other words, the application of the contextual approach in STEM education presupposes the organisation of internships in research laboratories and technology companies, the establishment of partnerships between educational institutions and industrial enterprises, the involvement of students in real scientific projects, and the use of immersion practices into communities of engineers and scientists through hackathons, active participation in STEM competitions, and scientific summer schools.

From the perspective of the socio-cultural context, STEM education is not limited to addressing "real problems"; rather, it entails a comprehensive rethinking of the educational environment, where scientific knowledge acquires meaning in relation to specific societal demands and civilizational challenges. For Ukraine, this implies, in particular, linking STEM education to issues of technological sovereignty, ecological security, and innovative development. In terms of implementing the contextual approach in STEM education, pedagogical tools may include the study of local ecological or technological problems, engaging local enterprises and organisations as clients for project tasks, conducting field research, and using real statistical data, scientific research results, and Internet resources as the basis for practice-oriented assignments.

Undoubtedly, among the identified approaches, the inquiry-driven approach occupies a significant place, as it entails direct modelling of the activities undertaken by scientists and engineers in their professional practice. The essence of the inquiry-driven approach rests on the assertion that learning is most effective and productive when students independently formulate questions, propose hypotheses, collect and analyse data, and draw well-founded conclusions. In other words, when they think and act as genuine researchers. The application of the inquiry-driven approach in STEM education substantiates not only the reproduction of

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scientific outputs (knowledge, formulas, theories) but also enables the realisation of the research process itself: from posing a research question, planning and organising scientific inquiry, to obtaining the final result.

The inquiry-driven approach in STEM education is particularly relevant, as it orients the learning process toward active investigation and the discovery of new knowledge through the use of scientific methods. Its essence lies in the fact that students do not merely assimilate ready-made information but independently formulate problems, generate hypotheses, conduct experiments, and analyse the results obtained. This creates conditions for the development of critical thinking, the ability to work with uncertainty, and the cultivation of research skills that are essential for contemporary STEM fields.

One of the key advantages of the inquiry-driven approach lies in the integration of theory and practice, since any research activity requires the application of a complex set of theoretical knowledge to organise scientific inquiry. This includes data processing as well as the use of theoretical methods (deduction, induction, analysis, synthesis, abstraction, concretisation, comparison and juxtaposition, modelling) and empirical methods (observation, experiment). These methods prove effective in the processes of problem-solving, the construction of new approaches, the modification of existing algorithms, and the development of original ideas.

Conclusions

Thus, based on the analysis of methodological approaches underlying the development and implementation of STEM education, it can be asserted that the systemic, learner-centred, activity-based, project-oriented, contextual, and inquiry-driven approaches together constitute an integrated and complementary methodological framework. The systemic approach is directed toward cultivating learners' ability to comprehend the integrity of systems, the interrelations among components, and the dynamics of their behaviour. The learner-centred approach emphasises the student as a subject with a unique cognitive profile, interests, needs, and self-efficacy. The activity-based approach substantiates the construction of learners' knowledge systems through active engagement rather than passive reception. The project-oriented approach transforms the educational process from preparation for future activity into the activity itself. The contextual approach renders learning meaningful by linking abstract knowledge with real-life experiences and specific social and technological challenges. The inquiry-driven approach enables the modelling of the very essence of scientific and engineering practice.

Prospects for further research include the study of the theoretical foundations of STEM education.

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