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STEM education: the theoretical foundations

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Abstract. At the beginning of the twenty-first century, STEM education has emerged as an integrative educational phenomenon that unites constructivist pedagogy, experiential and problem-based learning, as well as engineering and design thinking. The analysis of scholarly literature demonstrates that this theoretical core is stable, yet contemporary academic discourse reveals its expansion through integration with sustainable development, social interaction, and the cultivation of research competences. This dynamic and open character of STEM education defines its relevance and prospects for further inquiry. The article argues and synthesises the theoretical foundations underpinning STEM education, highlighting constructivism as a basis for active knowledge construction, experiential learning as a means of integrating theory and practice, and problem-based learning as a framework for transforming uncertainty into certainty through observation, hypothesis testing, and inferential reasoning. Engineering and design thinking are presented as complementary constructs that foster systemic vision, creativity, and user-orientation, ensuring that solutions are both functional and socially responsive. The research results emphasise that STEM education develops through disciplinary, interdisciplinary, and transdisciplinary integration, expanding opportunities for applying knowledge and skills to complex problems. It is characterised by contextuality, human-centredness, integrativity, experimentation, interdisciplinarity, creativity, and structured research processes. These features enable learners to generate, test, and refine ideas, create prototypes, and adopt optimal solutions collaboratively. The study concludes that STEM education equips learners with twenty-first-century competences such as critical, logical,

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creative, and innovative thinking, teamwork, communication, and adaptability, preparing them to meet societal challenges and contribute to the knowledge economy. The relevance of the research is substantiated by social demand, methodological novelty, practical significance, and forward-looking perspectives, making it strategically important for the modernisation of educational practices and the preparation of competitive specialists in the global context.

Keywords: STEM education, constructivism, experiential learning, problem-based learning, engineering thinking, design thinking, interdisciplinarity, innovation, social interaction.

STEM-освіта: теоретичні засади

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Анотація. На початку XXI століття STEM-освіта постає як інтегративне освітнє явище, що поєднує конструктивістську педагогіку, концепції досвідного та проблемного навчання, а також ідеї інженерного й дизайн-мислення. Аналіз наукової літератури засвідчує усталеність цього теоретичного ядра, водночас сучасний академічний дискурс демонструє його розширення через інтеграцію з концепціями сталого розвитку, соціальної взаємодії та формування дослідницьких компетентностей. Така динамічність і відкритість дослідницького поля визначають актуальність STEM-освіти та перспективи її подальшого розвитку. У статті аргументовано й узагальнено теоретичні засади STEM-освіти, зокрема конструктивізм як основу активного конструювання знань, досвідне навчання як засіб інтеграції теорії та практики, проблемне навчання як методологію трансформації невизначеності у визначеність через спостереження, висування та перевірку гіпотез. Інженерне та дизайн-мислення розглянуто як взаємодоповнюючі конструкти, що забезпечують системне бачення, креативність та орієнтацію на користувача, роблячи освітні рішення функціональними й соціально релевантними. Результати дослідження підкреслюють, що STEM-освіта розвивається на трьох рівнях інтеграції (дисциплінарному, міждисциплінарному та трансдисциплінарному), що розширює можливості застосування знань і навичок для розв'язання складних проблем. Вона характеризується контекстуальністю,

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людиноцентризмом, інтегративністю, експериментуванням, міждисциплінарністю, креативністю та структурованістю дослідницького процесу. Ці ознаки забезпечують здобувачам можливість генерувати, перевіряти й удосконалювати ідеї, створювати прототипи та колегіально ухвалювати оптимальні рішення. У висновках наголошено, що STEM-освіта формує ключові компетентності XXI століття: критичне, логічне, творче й інноваційне мислення, командну роботу, комунікацію та адаптивність, готуючи здобувачів до викликів сучасного суспільства та сприяючи розвитку економіки знань. Актуальність дослідження обґрунтовується соціальним запитом, методологічною новизною, практичною значущістю та перспективністю, що визначає його стратегічну роль у модернізації освітніх практик та підготовці конкурентоспроможних фахівців у глобальному контексті.

Ключові слова: STEM-освіта, конструктивізм, досвідне навчання, проблемне навчання, інженерне мислення, дизайн-мислення, міждисциплінарність, інноваційність, соціальна взаємодія, сталий розвиток.

Introduction

Topicality of the problem. At the beginning of the twenty-first century, STEM education has emerged as an integrative educational phenomenon that combines constructivist pedagogy, the concepts of experiential and problem-based learning, as well as the ideas of engineering and design thinking. At the same time, contemporary academic discourse demonstrates the expansion of this theoretical core through integration with the concepts of sustainable development, social interaction, and the cultivation of research competences. This reflects the constant dynamism and openness of the research field of STEM education. The relevance of the study is determined by several factors. First and foremost, there is a strong social demand, since STEM education responds to the challenges of society and the knowledge economy by preparing specialists capable of working with uncertainty and complex systems. Equally important is the methodological substantiation based on the combination of constructivism, experiential and problem-based learning with engineering and design thinking, which together provide a systemic framework for the formation of key twenty-first-century competences. The relevance of the study is further emphasised by its practical significance, as the integration of theory and practice through experiments, modelling, case studies, and prototyping fosters the development of critical thinking, creativity, and innovativeness. The forward-looking nature of the research is argued by the expansion of the theoretical core of STEM education in the direction of sustainable development, social interaction, and research abilities, which opens new horizons for further scholarly inquiry. Thus, the study is relevant not only because it systematises the basic theoretical foundations of STEM education, but also because it outlines promising directions for its development, which are of strategic importance for the modernisation of educational practices and the preparation of competitive specialists in the global context.

Literature review. The analysis of scholarly literature on the theoretical foundations of STEM education demonstrates that this research field is shaped at the intersection of constructivist pedagogy, learning theories, and the concepts of engineering and design thinking. At the same time, the international academic discourse proves to be considerably broader and more methodologically differentiated than the domestic one. The basic theoretical framework for understanding the nature of education is formed through studies of its essence and conceptual foundations. Scholars have undertaken some of the first systematic reflections on the notion of STEM in education, analysing its diverse conceptualisations and partnership models of implementation [3]. H. Gonzalez and J. Kuenzi outlined the strategic significance of STEM education in responding to societal challenges and labour market demands for qualified specialists [8]. These works established a conceptual basis that was subsequently developed in

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later studies. Y. Dosymov, E. Ergobek, S. Ramankulov and others represent a contemporary approach to fostering learners' research abilities within STEM education, which attests to the relevance and inexhaustibility of the topic in modern academic discourse [7].

Constructivism as a theoretical foundation of education has received extensive coverage in the scholarly literature. The classical works of J. Piaget on the psychology of intelligence substantiate the dynamic character of cognitive and intellectual development through the mechanisms of assimilation and accommodation of knowledge [12]. Developing the constructivist paradigm, K. S. Devi provided an analytical review of the constructivist approach to learning based on the concepts of Piaget and Vygotsky, emphasising their complementarity [4]. The connection between constructivism and STEM education has been directly examined by S. Akran and S. Aşiroğlu, who analysed teachers' perceptions of the constructivist approach as preparatory to STEM education [1].

A significant place in the theoretical substantiation of education is occupied by the concepts of experiential and problem-based learning. D. A. Kolb justified the concept of experiential learning as a specific organisation of the educational process grounded in learners' direct experience acquired through interaction with the real world [9]. John Dewey's concept of problem-based learning in the context of STEM education was analysed in detail by T. Koschmann, who revealed its potential for standardising the practice of problem-based learning [11]. The primary source is Dewey's own work, in which thinking is described as a process of transforming an indeterminate situation into a determinate one through successive acts of observation, hypothesis generation, and testing [5]. L. Vygotsky (1979) substantiates the role of the social context in personality formation and knowledge construction [14].

The aim of the article. The aim of the article is to argue and synthesise a set of theoretical foundations that underpin the development and implementation of STEM education.

Research results

STEM education is conceptualized as an educational phenomenon of integrative nature, the integration of which is realized at three levels: disciplinary, interdisciplinary, and transdisciplinary. These levels progressively expand the possibilities for applying knowledge and skills within the educational process. Disciplinary integration preserves the identity of individual sciences, interdisciplinary integration facilitates the search for common themes and methods, while transdisciplinary integration enables going beyond disciplinary boundaries and utilizing their potential to address complex problems.

To understand the essence of this phenomenon, it is necessary to analyse the theories and concepts that form its foundation, which substantiate both the development of STEM education and its implementation. It should be emphasized that the advancement of STEM education represents a response to contemporary societal challenges and the demand for specialists with relevant qualifications in the labour market [3; 7; 8]. Among the key theories, concepts, and ideas essential to its development and realization, we highlight constructivism, the concept of experiential learning, the concept of problem-based learning, and the ideas of fostering engineering and design thinking (see Fig. 1).

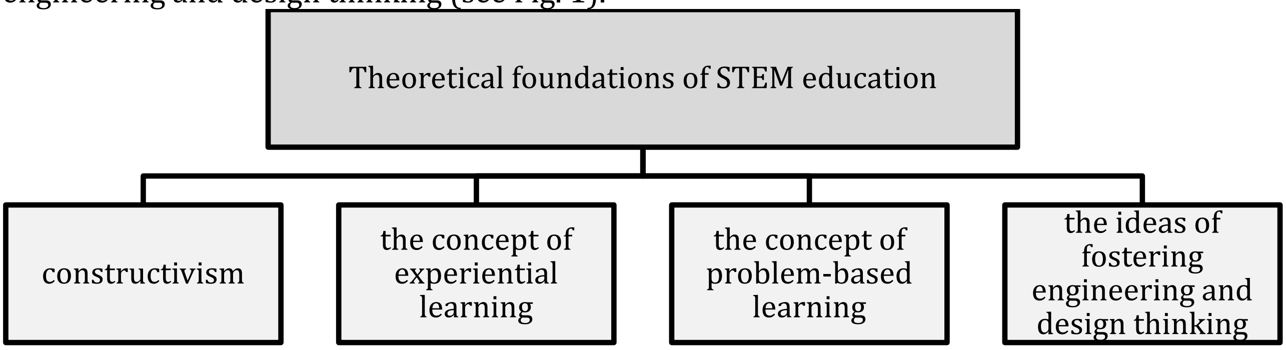

Fig. 1. Theoretical foundations of STEM education

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As evidenced by the analysis of scholarly and pedagogical sources [1; 6], in accordance with the ideas of constructivism, learning is understood as a process of enriching the learner's knowledge system, in which the learner assumes an active position. This active position is characterized by curiosity, interest, the desire to ask questions and seek answers, as well as the ability to analyse and interpret studied objects, processes, and phenomena. Such engagement contributes to the deepening, expansion, and enrichment of the learner's knowledge. Active cognition presupposes the formation of knowledge and understanding through authentic experiential learning, combining worldview, previously acquired knowledge and experience with new knowledge, and integrating them as the foundation for constructing one's own unique vision of the scientific picture of the world. In this context, it is logical to conclude that the human knowledge system is dynamic and in a state of continuous progression.

This position corresponds to the fundamental principles of constructivism [12], according to which cognitive and intellectual development is characterized as a dynamic process in which learning involves the acquisition of new information and its subsequent integration into already established cognitive constructs. According to Piaget, intellectual development can be conditionally divided into two stages [12]. The first stage is assimilation, which refers to the adaptation of new knowledge to the learner's existing knowledge system. The second stage involves the modification of this established system through its enrichment and expansion with newly acquired knowledge. "This requires that the new information be sufficiently demanding to create a disequilibrium in the existing schemas, which will adapt until a status of equilibrium is established. Hence, accommodations of new information will not be achieved if learning episodes are too demanding and differ too much from the student's existing schemas" [13, pp. 81–82].

It should be noted that constructivism is characterized by the presence of several directions, among which our scholarly interest lies in social constructivism. According to Vygotsky, personality development occurs within a social context that exerts a significant influence upon it. Undoubtedly, biological processes form the basis of human development; however, they play a secondary role [14]. The environment in which an individual is formed and comprehensively developed reflects a system of values, behavioural patterns, cultural traditions, and symbols, providing opportunities for adaptation to the conditions of social life and for the gradual formation of worldview, value orientations, and behaviour. In this context, the human knowledge system should be interpreted as dynamic and individual, shaped with regard to the specificity of a given context [2].

Such a substantiation of constructivism provides grounds for considering it one of the foundational concepts of STEM education, implemented through Piaget's interactive learning [14], Vygotsky's social interaction [14], Kolb's experiential learning [10], and Dewey's problem-based learning [11].

In summary, the core theses of constructivism underpin STEM education and can be formulated as follows: STEM education is based on experimental and experiential learning, which presupposes the active construction of a knowledge system grounded in learners' previously acquired knowledge and experience, with their gradual integration into the individual's knowledge framework and simultaneous verification in learning situations that closely approximate real-world conditions. STEM education is characterized by its contextual and experiential nature, implemented with consideration of the specific socio-cultural educational environment, which exerts a significant influence on the design and implementation of engineering solutions for addressing complex problems. Furthermore, STEM education entails not only the acquisition of knowledge and skills in the fields of technical and natural sciences but also aims at the development of key twenty-first century learning skills, including communication and teamwork, analysis and reflection, as well as critical, logical, creative, and innovative thinking (see Fig. 2).

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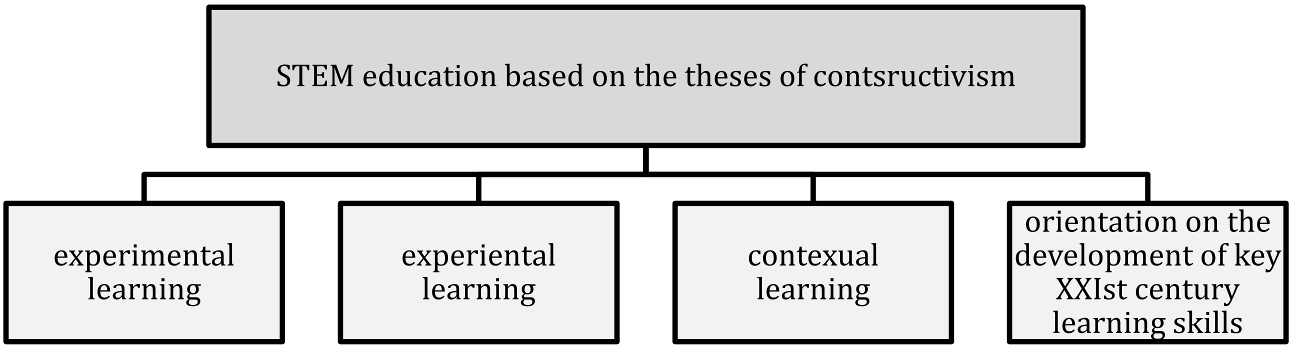

Fig. 2. STEM education based on the theses of constructivism

In the context of the problem under investigation, the concepts of interactive learning, substantiated by Piaget [12], and social interaction, advanced by Vygotsky [14], are equally significant. According to these concepts, social interaction and collaboration within a constructivist educational environment foster the development of thinking and provide access to new ideas. Learning that involves cooperation among learners, as well as between learners and the teacher, presupposes that participants in the educational process do not prioritize solely their own interests, preferences, and needs, but work collegially, taking into account the interests, preferences, and needs of others. Ensuring such balance has a direct impact on the achievement of collectively defined goals [4].

From the perspective of STEM education, the use of the potential of interactive learning and social interaction contributes to several key outcomes. First, it intensifies cognitive processes, since interaction provides access to new ideas, perspectives, problem-solving approaches, and alternative modes of thinking. This, in turn, stimulates the application of critical thinking skills, reflection on one’s own knowledge, and comprehension of the algorithms and mechanisms underlying complex research problems. Second, it fosters the ability to balance personal independence with responsibility, which is ensured in conditions of collegial learning that rely not only on one’s own knowledge but also on the knowledge, support, and contributions of other participants in the educational process, along with an awareness of one’s role in collective problem-solving. Third, it facilitates the formation and development of social competencies (teamwork, communication, conflict prevention and resolution) without which collaboration in a group is impossible, and consequently, the implementation of projects, collective experimentation, and the search for rational solutions from a multidisciplinary perspective cannot be achieved. Finally, it promotes the development of collegial thinking and the construction of a shared knowledge system, which can subsequently be applied to ensure the effectiveness of collective task resolution (see Fig. 3).

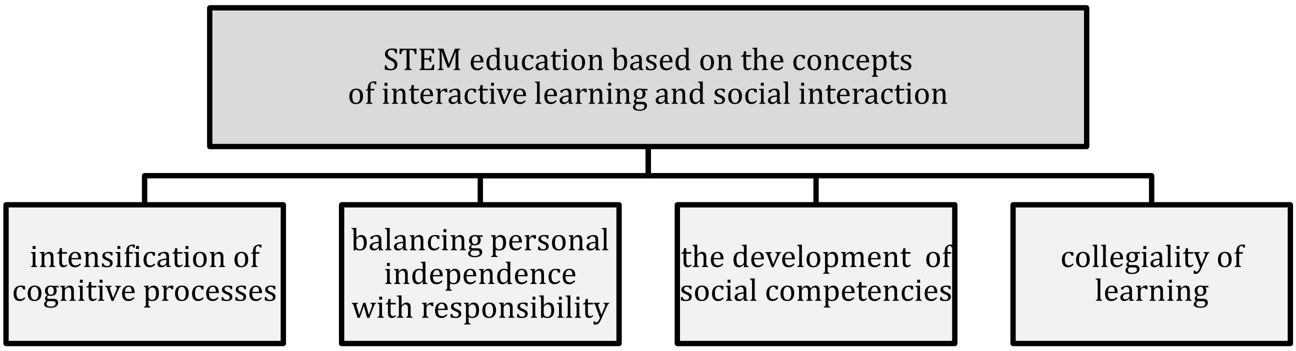

Fig. 3. STEM education based on the concepts of interactive learning and social interaction

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In the context of our study, it is important to address Kolb's concept of experiential learning [9]. According to the scholar, experiential learning should be understood as a specific organisation of the learning process, the foundation of which lies in the use of learners' direct experience [9]. Unlike traditional learning, which is characterised by lectures, seminars, practical and laboratory sessions, the concept of experiential learning emphasises the appropriateness of utilising learners' immediate experience formed through interaction with the real world. This involves the activation of sensory perception and practical actions of learners within a particular context, serving as a key source of knowledge. Contemporary educational practice demonstrates that the integration and balance of theoretical and practical training of specialists are achieved through internships in enterprises and business companies, the implementation of practical research, the use and analysis of case studies, simulation and modelling, as well as the application of gamification potential.

An essential component of the concept is its connection with lifelong learning. In this regard, experiential learning is conceived as a continuous process of acquiring knowledge from life situations, controlled by the individual. Such an approach fosters the ability for independent inquiry, critical reflection on one's own experience, and its integration into the knowledge system. Thus, experiential learning not only complements traditional academic practices but also creates conditions for the development of autonomy, responsibility, and innovativeness among learners.

Thus, grounding STEM education in the principles of Kolb's experiential learning concept substantiates the application of several key practices: the use of learners' direct experience as a source of knowledge, based on active scientific exploration of the world in practice-oriented situations (experiments, modelling, simulations, case studies), where sensory perception and practical actions become the foundation for knowledge formation; the integration and balance of theory and practice, as well as the development of skills and abilities to apply knowledge in practice through the implementation of research projects, business case analysis, gamification, and other innovative methods; and the cultivation of autonomy and innovativeness in learners' educational activity, which contributes to the development of responsibility, creativity, and entrepreneurial thinking necessary for functioning in conditions of rapid technological change (see Fig. 4).

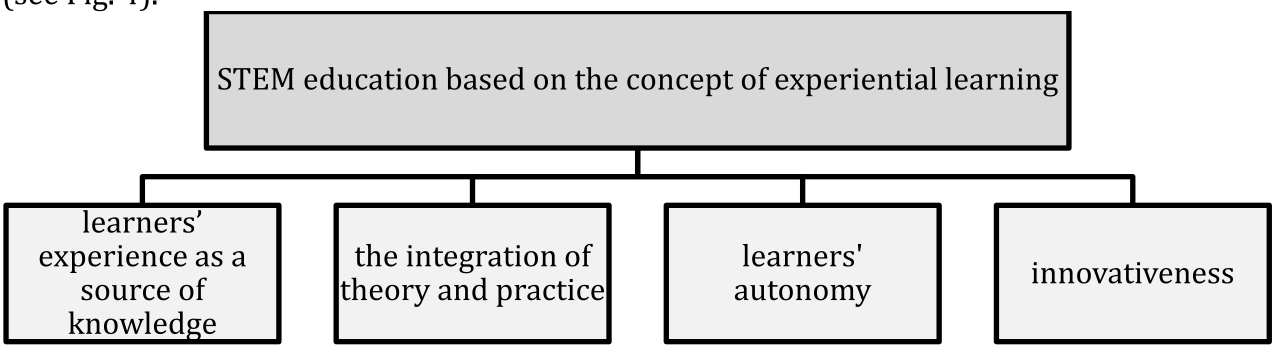

Fig. 4. STEM education based on the concept of experiential learning

For STEM education, John Dewey's concept of problem-based learning [5] is of particular importance. Dewey argued that the process of cognition encompasses several successive actions, beginning with the identification of "uncertainty" and its gradual transformation into the "certainty" of a research problem. "The conditions discovered, accordingly, in and by operational observation, constitute the conditions of the problem with which further inquiry is engaged; for data, on this view, are always data of some specific problem and hence are not given ready-made to an inquiry but are determined in and by it. The point previously stated, that propositions about data are not cases of knowledge but means of attaining it, is so obviously an integral part of this view that I say nothing further about it in this connection" [5, p. 181].

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The definition of the essence of a problem facilitates the delineation of its contours through repeated acts of observation, thereby generating possible options for its resolution. These options represent potential interpretations of the data obtained, while the process of thinking consists in their elaboration and refinement. When such options are tested against empirical evidence, they become the subject of inferential propositions, which do not constitute knowledge per se but serve as instruments for its attainment. At the same time, they possess an operational character, insofar as they initiate new experimental observations that enable both the verification of prior hypotheses and the formulation of new ones, or the modification of existing solutions. This process continues until the indeterminate situation is transformed into a determinate one [11].

On the basis of the foregoing, we conclude that problem-based learning holds significant importance for the implementation of STEM education, as it is oriented toward: the organization of the cognitive process in which the "unknown" is transformed into the "known" through the recognition of an "indeterminate situation," the formulation of conditions and criteria for its resolution, thereby fostering the ability to work with uncertainty and complex systems; the use of research methods to construct a system of knowledge through observation, experimentation, and engagement with data in laboratory investigations, modelling, and data analysis, which entails identifying regularities, testing hypotheses by means of critical thinking and scientific inquiry skills; and the utilization of the dynamic nature of knowledge and collegial problem-solving based on the analysis of multiple possible interpretations of data, which are refined and verified, forming the foundation for collaborative development of creative and innovative solutions, as well as the modification of established algorithms and previously applied approaches (see Fig. 5).

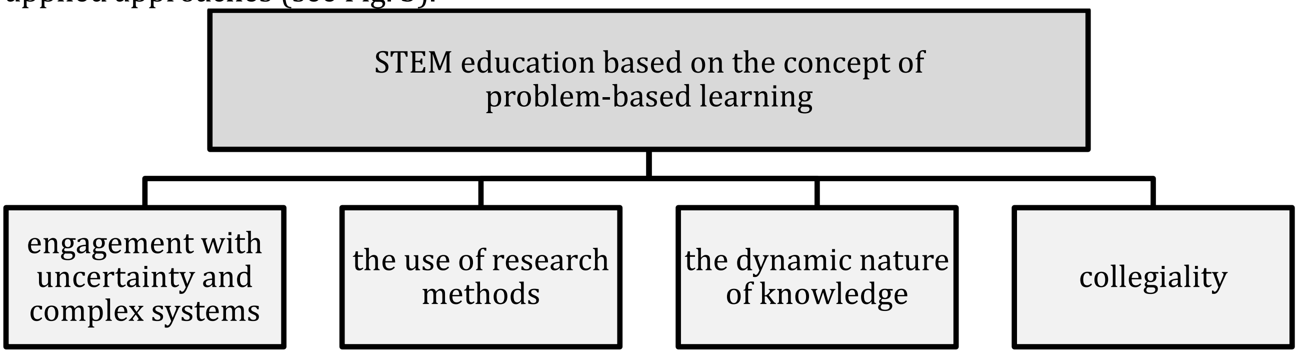

Fig. 5. STEM education based on the concept of problem-based learning

Given the underlying reasons for the development of STEM education and its demand as a foundation for societal progress and the knowledge economy, it is appropriate to consider the ideas of engineering thinking and design thinking. These two modes of thought are complementary and interconnected conceptual constructs. From their perspective, problem-solving is not reduced to the search for a single solution but entails the generation of multiple innovative solutions and the application of the one deemed most optimal. Indeed, the generation of a multiplicity of possible solutions requires skills such as applying a systemic vision to problem-solving, grasping the essence of the problem, decomposing complex tasks, and recognizing both the availability and limitations of resources that condition the search for the most effective solution. The integration of engineering thinking and design thinking is reflected in the notion of "engineering design processes," which encompass a cyclical sequence of stages: problem identification and specification, research, idea generation, prototyping, analysis, and reflection.

A distinctive feature of engineering thinking and design thinking is their transdisciplinarity, which presupposes mastery of a complex body of knowledge drawn from diverse scientific domains, including not only mathematics, engineering, physics, and chemistry, but also a range of disciplines within the social and human sciences. Such reasoning

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is grounded in the understanding that contemporary engineering solutions must be not only functional but also responsive to the social demands of society. Accordingly, it is logical to conclude that STEM education, founded upon the ideas of engineering thinking and design thinking, entails creativity, analytical capacity, and user orientation, taking into account preferences, interests, and needs. Its defining characteristics include: anthropocentrism, which requires consideration of interests, needs, and experiences that play a decisive role in decision-making within specific contexts; integrativity and experimentation, which enable the generation and testing of ideas, the creation and refinement of prototypes, the identification and correction of shortcomings, and the overcoming of challenges regarded as integral elements of the learning system; interdisciplinarity and creativity, which guide the research process and problem-solving toward innovative solutions from multiple perspectives; and the structured nature of the research process, realized through a sequence of stages: recognition of user needs, identification and specification of the research problem, idea generation, prototyping, testing, adjustment, and adoption of the final optimal solution (see Fig. 6).

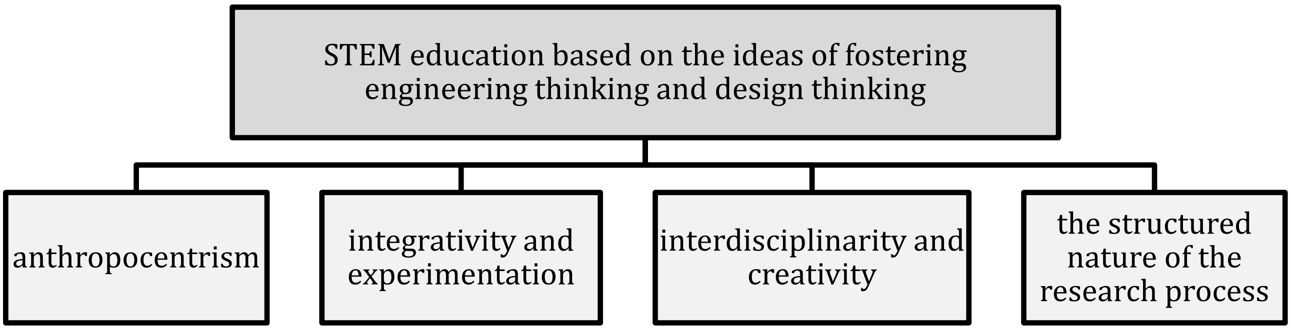

Fig. 6. STEM education based on the ideas of fostering engineering thinking and design thinking

Thus, based on the analysis of the theoretical foundations underlying STEM education, we may assert that constructivism emphasizes the active role of learners in the educational process. Access to new ideas and the development of key competencies for learning in the twenty-first century are ensured through the organization of interactive learning and social interaction. The concept of experiential learning highlights the importance of applying learners' prior experience, while problem-based learning fosters the formation and development of research competence. The incorporation of the ideas of engineering thinking and design thinking within STEM education substantiates the application of a systemic approach: from the generation of multiple ideas to their comprehensive implementation.

Conclusions

STEM education is an integrative phenomenon that develops through disciplinary, interdisciplinary, and transdisciplinary approaches, expanding the possibilities of applying knowledge and skills to solve complex problems. Constructivism emphasizes the active role of learners in building knowledge through assimilation, accommodation, and social interaction, highlighting the dynamic and contextual nature of learning. Experiential learning strengthens STEM education by using learners' direct experience as a source of knowledge, balancing theory and practice, and fostering autonomy, responsibility, and innovation. Problem-based learning is essential because it transforms uncertainty into certainty through observation, hypothesis testing, and inferential reasoning, thereby developing research competence, critical thinking, and the ability to work with uncertainty and complex systems. Engineering thinking and design thinking complement each other by promoting systemic vision, decomposition of complex tasks, and awareness of resources, ensuring that solutions are both functional and socially relevant. STEM education is defined by anthropocentrism, integrativity, experimentation,

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interdisciplinarity, creativity, and structured research processes, which enable learners to generate, test, and refine ideas, create prototypes, and adopt optimal solutions collaboratively. Altogether, STEM education provides learners with twenty-first century competencies such as critical, creative, and innovative thinking, teamwork, communication, and adaptability, preparing them to meet societal challenges and contribute to the knowledge economy.

The analysis of the consulted body of scholarly sources indicates the stability of the theoretical core of STEM education, which is constituted by constructivism, the concepts of experiential and problem-based learning, as well as the ideas of engineering and design thinking. At the same time, contemporary academic discourse demonstrates a consistent expansion of this core through its integration with the concepts of sustainable development, social interaction, and the cultivation of research abilities, thereby defining promising directions for further inquiry.

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