A Review of Research on Fostering Engineering Thinking in STEM Education

Wenyi Zhang

Shanghai Normal University, China

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Abstract: STEM education is problem solving, engineering design, and built product-based learning that is interdisciplinary and open-ended. Students apply knowledge from science, engineering, technology, mathematics, and other disciplines to solve problems innovatively in engineering practices, driven by real-world problems and built products. Students cultivate practical thinking, stimulate design thinking, and enable constructive thinking in the activities of solving real-world problems, engineering design and building products, which can achieve the goal of cultivating engineering thinking.

1. Introduction

Engineering thinking is the thinking formed in the process of design, research, and practice of engineering, the key is to use various knowledge and ways to solve real problems, with the characteristics of practical, design, and construction (Yang et.al. 2010). STEM is the acronym of Science, Technology, Engineering, Mathematics. In Jeff Radloff's (2016) publication, he considers that there are five characteristics integrated the STEM: (a) the primary learning goal is based on Math and Science. (b) using the engineering practices and the engineering design to combine Science and Math and using it as content. (c) using the Math and Science as a tool to solve the engineering problem. (d) emphasizing the latest science skill during the class. (e) the engineering issues evolving some real-world problems and solving it by teamwork (Lin et.al., 2021).

Engineering thinking has received increasing attention from the education community, but the effectiveness of engineering thinking education in primary and secondary schools is not as good as it should be. Not all students are able to choose the optimal solution to the issue but the process that the children try to solve the problem by modeling and analyzing the feasibility of the plane can cultivate the children's ability to model and evaluate the idea which are quite important to the engineering thinking. Although many factors are affecting the effectiveness of engineering thinking education, the lack of curriculum carriers for cultivating engineering thinking is the main factor. Cultivating engineering thinking can help the children to gain inquisitive mindset, solving problems by using different methods. It also helps connect the discipline knowledge with the real-life problem which can make the children realize the meaning of learning and improve their ability to solve complex issue in a more systematic way. In this passage, the paper will analyze the structure and characteristics of engineering thinking and analyze some relative cases to provide some guidance to the stem curriculum design.

2. Literature Review

STEM Education Research - New Concerns about Curriculum Reform at the K-12 level in the United States introduces three parts of the developmental lineage of STEM education, the current state of education, and STEM teacher training in the United States (Fan, 2011). The previous stem education could be traced back to STS (Science, Technology, Social) and STSE (Science, Technology, Social life, Environment). The former attaches importance to society on the basis of science and technology education, while the latter attaches importance to environment on the basis of science and technology education. However, the neglect of mathematics and engineering leads to the lack of national mathematics engineering talents (Lin et.al., 2021). Due to the problem above, China introduces the work done by educational management organizations in the United States and other countries in the implementation and promotion of STEM education based on the relevant investigation, policy release, funding sponsorship and international cooperation of American educational management organizations in the implementation and promotion of STEM education. STEM: A Top Priority for U.S. Education Strategy analyzes the reasons for STEM education in the U.S., and compares the bills and reports related to STEM education in the U.S. from 1986 to 2012 (Zhao,2012). Preparing the Next Generation of stem innovators: Identifying and Developing our Nation's Human Capital," published by the National Science Board in 2010, is described in detail in Cultivating Outstanding Innovators in Science, Technology, Engineering, and Mathematics (STEM). Developing our Nation's Human Capital, summarizes the research as providing exceptional opportunities for outstanding innovators, casting a wide net for talent selection strategies, and creating an ecological support system that is conducive to talent growth (Wan & Zhang, 2012).

As early as the 1980s, Qian Xuesen, a famous scholar in China, proposed the idea of establishing a science of thinking. It believes that exploring the laws and methods of thinking is a necessary path for the development of human knowledge, and puts forward its vision of the basic principles, theoretical system, and structural framework of the science of thinking. Exploration of Engineering Thinking analyzed engineering and its essence, elaborated the meaning, essential characteristics, activity process, and types of thinking of engineering thinking, discussed the great significance of engineering thinking in engineering activities, advocated active development of innovative thinking of engineering subjects, and called for opening a new era of engineering thinking with innovative education as the source and engineering practice as the basis (Zhao, 2006).

The engineering thinking education does not put emphasis on modeling and analysis. It lacks the criteria of accessing the creation of the project. Even though let the students grade the other groups which is too subjective and could not embody the true quality of the projects because it just focuses on the conclusion of the work. However, the process of collecting information, modeling and analyzing the viability of the project is equally important in the stem class, especially in cultivating engineering thinking. The main goal is to cultivate a large number of high-quality engineering talents with strong innovation ability and adapt to the needs of economic and social development, to build an innovative country, realize industrialization and modernization, and enhance the core competitiveness and comprehensive national power of China. In "Discerning Engineering Thinking in Information Technology Curriculum", the triadic theory of "science-technology-engineering" is used to examine the relationship between engineering and science and technology, to explain the characteristics of engineering thinking, to analyze the development of information technology curriculum and teaching contents from the perspective of engineering thinking, and to propose It also proposes to cultivate students' engineering thinking through primary and secondary school information technology curriculum (Wang, 2012).

3. Concept Definition

3.1 Stem Education

In 1983, the U.S. federal government issued the document "A Nation at Risk: The Education Reform Imperative" for the country to stay ahead in the global economic competition, thus kicking off the U.S. education reform. Stem is made up of the Science, Technology, Engineering and Mathematics. It is believed that Stem education refers to the learning and teaching between any two or more of the four STEM subjects, or between one STEM subject and one or more other subjects. The White Paper (2017) on STEM Education in China published in China views STEM education as interdisciplinary and defines it as an organic integration of science, technology, engineering, and mathematics, with a project learning, problem-solving oriented curriculum organization.

In China, Science of full-time compulsory education (Curriculum Standards of Grades 3-6) points out that elementary science course is a science enlightenment course aimed at cultivating primary school students' scientific quality. Students should experience inquiry-based learning activities and teachers should cultivate students' curiosity and desire for inquiry, develop their understanding of the nature of science and enable them to learn strategies of exploring and solving problems. The aim is to cultivate high-tech talents with an innovative spirit (Fan, 2011).

3.2 Engineering thinking

According to the report "Engineering in K-12 Education: Understanding the Present and Improving the Future" by the National Academy of Engineering (NAE), engineering thinking is the "habit of thinking" of engineering, which includes: systems thinking, creativity, optimism, collaboration, communication and ethical considerations. The so-called engineering thinking, as the name implies, is the unique way of thinking formed by people in the process of engineering activities and engineering researches, which is defined as "professional planning entity thinking". During the elementary education period, we do not expect students to work out a complex engineering project or find the optimal solution to engineering project. We want to cultivate their thinking model of how to solve engineering problem, which is called engineering thinking. Engineering thinking is a way of thinking for the transformation of the world, which has a strong purpose and value (Xu, 2002).

4. Theoratical Foundation

4.1 An integrated view of STEM education.

American experts and scholars mainly hold two attitudes towards the connotation of the concept of STEM education: the development of STEM education in the United States is dominated by integration and coexistence of sub-discipline, but scholars in the field of education prefer integrated STEM education. American scholar Sanders (2009) emphasized that the four-letter acronym "STEM" cannot fully represent STEM education, and the STEM that ignores "education" is more focused on the field of work of scientists and mathematicians, therefore, the concept of "integrated STEM education" (integrated STEM education) has emerged, highlighting the unique feature of STEM education – integration (Sanders,2009). Nowardays, the application of the STEM is extensive. It ranges from the Primary education to the higher education and they put emphasis on the gender difference. According to the research made by Evila Piva (2021), it shows that the STEM education may benefit the women in entrepreneurial entry. However, there was research indicated that the male advantages exist in the STEM education. There are multiple factors contributes to this result, such as, education system, education environment and opportunity of labor market. (Hägglund &Leuze, 2021). The concept of STEM in China was introduced from America and adjust the teaching method in order to allow the STEM being adapt to Chinese education. STEM education in China also leans more towards the integrative style. Fu Qian et al. (2016) argue that any problem we encounter in the real world, no matter how difficult or easy, cannot be solved with the help of knowledge from only one domain, but is often an integration of knowledge from several domains; therefore, the relevance of STEM education is to develop students' ability to solve problems by integrating knowledge from science, technology, engineering, mathematics and other domains (Fu Qian &Liu Pengfei., 2016). The core research of the Chinese STEM education is focused on the primary school, senior high school and college school and putting emphasis on learning the American STEM education and creation maker, teaching method, teaching effect, teaching strategies, etc. (Le, JJ., 2021). Our Professor Yu Xiaoya (2018) has pointed out that the implementation of STEM education is a parallel of two lines of scientific inquiry process and engineering design process (Yu, 2018). The learning outcomes of learners in STEM education can be divided into two dimensions, on the one hand, the knowledge content internalized by learners and on the other hand, the works developed, which correspond to the scientific inquiry process and the engineering design process, respectively.

The purpose of the STEM class is both let students gain insight of the knowledge and cultivate the students the ability of solving the problem by using engineering thinking. However, the class designs in China about engineering designs focus on the difficulty of the class and lack the association to the knowledge in relevant discipline. Students do not be equipped with relevant knowledge so it is difficult for them to be creative when they are accomplishing the program (Ksenia &Audrey, 2014). Based on the context-integrated STEM education theory, this study designs an activity model for developing students' engineering thinking skills, so that students can conduct scientific research, learn about physics, mathematics, and other fields, and explore the scientific principles involved in thematic engineering activities by solving engineering problems in thematic engineering activity contexts.

4.2 Engineering Methodology

Human thoughts, emotions, aesthetics, knowledge and skills, etc., can be reflected in engineering. In an engineering project, each participant plays a different role, each in its own way, such as engineering decision maker, designer, implementer, etc. Each role does not only perform physical work, but also more thinking activities. At the beginning of the project, the engineering participants must analyze the project systematically and need to control the project qualitatively and quantitatively as a whole from six aspects: problem faced, objective and goal, solution, model, evaluation, and decision maker (Yin et.al., 2007), to come up with the optimal solution to the problem. The problem faced can actually be understood as the research object, and the team led by designers and decision makers should consider the connection and contradiction between the real conditions and the engineering problem to be solved, so as to prepare for the subsequent work. The engineering thinking is related, permeated and different from scientific thinking and technical thinking. "Engineering" is not only different from traditional engineering education, but also not limited to the teaching of engineering thinking. Cultivating students' engineering thinking is not the only goal of STEM courses. Instead, it takes "engineering" as the center, providing a framework and creating an environment for the cultivation of engineering thinking and other higher-order thinking (Sun & He, 2021). During the process of solving issues, Students can make comprehensive practical application of abstract knowledge in different disciplines, so as to generate more interest and deeper understanding of subject knowledge. The model is composed of the various engineering units included in the whole project and the relationship between them, which can be understood as the basic framework for solving the problem, and specific solutions can be brought into the model for testing. Evaluation is the process of measuring between the engineering inputs and outputs (final results) of different solutions, and requires a combination of engineering factors such as functionality, reliability, and cost to determine whether the solution can accomplish its goals efficiently and effectively. The decision maker is the key to a project and is responsible for the coordination of the relationship between each factor within the entire project in order to promote the development of the project activities.

Engineering thinking is a kind of higher-order thinking, because engineering activities involve people with individuality and different external environment, so engineering is not only the integration of various technologies, but should consider the specific process of implementing engineering activities. One of the characteristics of engineering thinking is "concept mode innovation", and the mode innovation comes from the planning and design of engineering. The method of solving engineering problem is very important in cultivating engineering thinking. The key point of solving the engineering problem is not found the optimal solution but allowing the students to solve the problem by modeling and analyzing the feasibility of the plane can cultivate the children's ability to model and evaluate the idea which are quite important to the engineering thinking. During problem solving, you can repeat these steps over and over again, even between steps, until you find the optimal solution. Engineering concept and engineering decision stage in engineering concept is mainly to clarify what kind of engineering to be carried out, which leads to engineering decision - to determine the goal of practice, choose the way of practice, there is often more than one way of practice, how to choose a most effective and reasonable way to start the project, at this time highlights the necessity of decision-making. Engineering planning is a comprehensive planning process for future engineering tasks, process, effect, environment and engineering implementation steps, while engineering design is the concretization of the planning results and expresses the abstract idea in the form of design drawings, engineering planning and design is a unified stage. Engineering organization and control will run through the whole project, and will always adjust the engineering program for the problems that appear in the project, which reflects the dynamic nature of engineering activities. Engineering implementation is a process of transforming abstractions such as ideas and design solutions into concrete man-made objects. Engineering operation and evaluation are the unification of two processes. After the implementation link is completed and the engineering results are obtained, the operation stage is entered and the evaluation is launched, which is a test of whether the engineering decision is correct, the engineering design is reasonable and the engineering implementation is reliable. Engineering renewal and renovation is to make partial adjustment or complete reconstruction on the basis of the original project according to the degree of completion of engineering tasks after the operation and evaluation of engineering results.

4.3 Kolodne double-loop model

The Kulodona double-loop model is a specific pedagogical model in the Design-Based Learning (DBL) theory. The main task of design-based learning is for learners to design and create an engineering product that fits the topic based on a challenging task assigned by the teacher (Doppelt et.al.,2009), and the whole process of design and learning requires learners to not only apply their previous knowledge and skills, but also acquire new knowledge and skills, establish logical connections between old and new knowledge, and use the knowledge to analyze and reason to develop learners' higher-order thinking skills (Design Challenge Curriculum). Design-based learning theory can assist learners to use multidisciplinary knowledge to solve "good" or "bad" problems (S.M.G A et.al., 2011) and help them to develop a series of higher-order thinking skills such as problem-solving, teamwork, and engineering design (Ayub, 2015). Design-based learning first originated with Professor Kulodona's team at the Georgia Institute of Technology's College of Education Sciences (Fan, 2015) as a pedagogical approach developed for secondary science education that integrates design activities into science lessons, providing opportunities for learners to continuously build, evaluate, discuss, and revise original knowledge concepts and completed work (Barron et.al., 2017).

In the continuous practice and refinement of design-based learning theory, the Crotona team proposed the Kulodona double-loop model, also known as the design-based scientific inquiry cycle model. The Kulodona double-loop model places the scientific inquiry process in the context of design activities, including the "design/redesign" and "investigation and exploration" cycles, and emphasizes the need to clarify "what needs to be known" and "what needs to be done" at the beginning of the activity. "Need to know" corresponds to the "Investigate and Explore" cycle. The "Design/Redesign" cycle consists of six steps: understand the challenge, design a plan, show and share, model and test, analyze and explain, and show and share again." The Investigate and Explore cycle consists of defining the problem, making a hypothesis, designing an investigation plan, conducting the investigation, analyzing the results, and presenting and sharing.

Both the scientific inquiry perspective and the activity design perspective begin with identifying the problem that needs to be solved and then proposing a solution to it. In addition to the self-loop of two independent loops, the loop between the "need to do" and "need to know" processes can be freely jumped according to the actual situation, and the loop between the two processes can be carried out. For example, if a learner is in process "modeling and testing" of process "design/redesign" and finds that he or she needs new knowledge and skills, he or she can go directly to process "investigation and exploration" to acquire new knowledge or skills. The two cycles of the Kulodona double-loop model complement each other, with cycle "investigate and explore" providing the theoretical support for cycle "design/redesign" and cycle "design/redesign" practicing cycle "investigate and explore". In the continuous iteration of the two cycles, the problem solution spirals upward, and the learner acquires both scientific knowledge and practical skills.

5. Teaching Strategies for Cultivating Engineering Thinking Based on STEM Concepts

5.1 Cultivating practical thinking in problem-solving

Engineering education is a kind of artificial system and an open complex artificial system. It advocates a systematic approach to engineering education. It puts forward that "systematic mode" is an organic entirety formed by the definite mode of all systematic concepts. Engineering thinking is meant to cultivate students’ ability of modeling and analyzing the feasibility of the plane. Stem education is an integration of Science, Technology, Engineering and Math. Students exercise planning in problem-solving, identify the feasibility of projects in real-life scenarios, and firm up the value of engineering in task-driven situations, and STEM education is an effective way to cultivate practical thinking (Li, 2015).

5.1.1 Problem solving: exercising planning thinking

Thinking activity is, from the perspective of psychology, realized by means of speech, representation and action, and is an indirect reflection of the essence and laws of objective things (Holly K. Osburn & Michael D. Mumford, 2006). Humans have two different kinds of thinking activities, cognitive and planning. Thinking about what the object itself is like is cognitive thinking; thinking about how to make something happen is planning thinking. Planned thinking in engineering refers to the mobilization and use of various ways of thinking in solving real-world problems, and the transportation and integration of problems in a holistic, multi-level, and multi-faceted manner to achieve solutions to engineering problems (Li, 2015). The problems that students have to face in the classroom are very different from the problems they have to face in real life; regular classrooms face more closed, well-structured problems, i.e., good-constructed problems, while more often they encounter open, vaguely structured problems, i.e., bad-constructed problems, in daily life. Well-constructed problems often require only a single solution, and the skills required to solve them are more limited. Teachers lack a guidance and structure when they are teaching students. There is not a specific method in teaching and most teachers just put the planning element into their education plans without teaching the students how to make plans and motivating their creativity. Students are expected to choose what they think is the best solution, implement the solution, and may have to continually modify the solution as they work through the problem. During this process, students are constantly considering the feasibility, workability, and operational aspects of the solution, which not only facilitates problem-solving but also exercises planning thinking. For example, in the lesson "Making a Wind-Powered Cart," students should be guided to think about the following questions: What materials can be chosen to make a wind-powered cart? What are some things that use wind for power? How do you make a cart? What forces are applied to the cart while it is in motion? How can the cart be made to have less resistance and more thrust? What are some ways to reduce the friction between the cart and the ground? What can be done to make the body stronger? How could a wind-powered cart be tested? In this way, students are forced to consider the above set of questions at the outset. These questions not only help students to better complete the subsequent stages of design and production but also motivate them to continuously think about the feasibility and operability of making the cart, which helps them to exercise their planning thinking.

5.1.2 Real-life situations: discerning feasible thinking

How many times can you fold a piece of A4 paper? Some children answered countless times, others tried their hands and could only fold it 7 times. The former is a theoretical answer based on ideal values, not on reality, and may not be achievable. The latter is based on a real situation and takes into account its "realism", "achievability" and "feasibility", which is engineering thinking. In the real class, the different students may have different feasible thinking. Some students would answer the scientific question based on realistic feasible thinking that means they consider whether the answers of the questions are based on the scientific reason. The other students would answer the question based on their imagination. For example, in the lesson "making a model of the solar system", to reduce the distance between the eight planets and the sun and reduce the diameter of the eight planets to make the model, if the distance is reduced by 1013, then the farthest from the sun Neptune is about 45 cm, the nearest Mercury distance is about 0.6 cm, students in the classroom production is feasible. But if the diameter of the eight stars is also reduced by 1013, then the smallest Mercury is only 0.00005 cm in diameter, which is only one-thousandth of the diameter of a hair, so students can't make it. Thus, for students to make a model of the solar system within the constraints of the classroom, the distances of the eight planets from the sun and the diameters of the eight planets would have to be scaled down at different scales. If the distances of the eight planets from the sun were reduced by 1013 and the diameters of the eight planets were reduced by 109, so that the reduction was done at two different scales, a model of the solar system of appropriate size and distance could be created. STEM education learning activities based on real-life situations make it necessary for students to discern the "realism," "achievability," and "feasibility" of technology, cost, materials, and site when making products. Only by fully and comprehensively considering these constraints can students complete their products.

5.1.3 Task-driven: firm up value-based thinking

Engineering thinking is a value-oriented type of thinking that aims to meet social needs and achieve and create greater value (Li, 2015). STEM education sets realistic goal tasks, both to meet social needs and to achieve and create greater value. Students gain real-life experiences and grow socially while completing the target tasks. For example, in the Designing and Making Thermoses STEM education project (Wu, 2017), a virtual scenario can be set up when introducing the learning task: a student from a primary school in Linxia (our twinned school) wrote a letter to our class saying that she brings a bottle of water to school every morning, but by the time she arrives at school, the water is frozen and she cannot drink it at all, and there is no mall nearby that sells thermoses. She has materials such as foam board, Styrofoam, cotton, aluminum foil, and felt, and has tried to make a thermos with these materials, but the insulation is not good. Can you help her make a cup with better insulation? Since Stem is an integrated discipline, which coalesce the Science, Technology, Engineering and Mathematics, the Stem class should be involved multiple value based-thinking in the class. STEM education activities are those that aim to solve real-world problems and meet social needs, and can firm up the value of students' engineering thinking.

5.2 Stimulating design thinking in engineering design

The design thinking is defined as ‘empathize-define-ideate-prototype-test’. These steps of design thinking are based on the collection and acquisition of concrete facts and information to understand the problems reflected in the information, forming abstract questions, focusing on the core appeal of the target and having the prototype solution. STEM education is design-based learning, and engineering design becomes the main content of learning, a vehicle for thinking training, and an effective way to develop design-based thinking.

5.2.1 Open Learning: Developing Creative Thinking

Creative thinking is the ability to produce responses that are both original and useful. Like other complex thinking processes, creative thinking draws on higher-order cognitive resources. The impacts of feedback, cognitive load, and self-efficacy on traditional complex thinking activities are well documented. However, little is known about how these factors influence creative thinking, which is unique in its requirement of originality. We investigated the impacts of social comparison performance feedback and creative self-efficacy on cognitive load during two creative thinking (divergent thinking) tasks. Positive feedback was associated with lower cognitive load compared to negative feedback. Implications for providing feedback to students during creative thinking tasks are discussed (Redifer et.al., 2017). There are four factors that may contribute to the cultivation of the creative thinking according to the construal level theory, which are distant in times, abstraction of the description, special distance, probability of the issue occurrence. Ksenia S. Z and Audrey C. R (2014) made an experience of testing whether these factors would affect children’s creativity. They chose some proximal topics and distal topics to see whether the proximal or distal academic content would affect the children’s creativity. In the end, they found that the consequence of the experience was opposite to the construal level theory. The Ksenia and Audrey assumed that it may be caused by the knowledge background of the students because the students took part in this experiment came from the low-income families which may lead to their lack of the knowledge of the distal accident content. They lacked the insight of the distal accident which restricted their creativity. When using the construal level theory in the class to cultivate students’ creativity, the teacher should pay attention to students’ knowledge background. The education background of the students contributes to whether they have enough knowledge which is relevant to the teaching topics to give a full play of their creativity.

5.2.2 Innovative thinking of students

The Chinese STEM education was introduced from American. There are many teaching theories were learned from American STEM education and Chinese stem made some adjustment based on Chinese students learning rules and Chinese education policy. Chinese education is switching their teaching principle from the formal principal that teacher is the central role of the class and teaching objectives is only teaching the knowledge of the students to the present teaching principal of both teachers and students who are central roles of the class. Solving the real-world problem and cultivating innovative thinking are essential parts of the technical ability, which provides the society with the practical talent. America developed the STEM education earlier than China so America notices that cultivating student's innovative thinking is crucial to developing all-round talent so there are many relevant researches. In the research of Ksenia S. Z and Audrey C. R (2014), the two researchers put the students into two kinds of class which are the distal topic class and the proximal topics class. In the construal level theory, the distal topic arouses student innovation thinking better. However, this research found out that children's knowledge background would restrain their development when the researches put this theory into practice because the lack of the knowledge which is relevant to teaching content which would decrease the association thinking, which leads to the deficiency of the innovation thinking. The research guides us to test students' previous learned knowledge and adjust teaching content which the students have correlative information. Engineering design is a non-linear and somewhat disorganized process that cannot be a "one-shot deal" and failure can occur, and testing the product is not the end of engineering design (Wu, 2017). Students test to find the causes of failure, try again and again and iterate to improve and refine their work.

5.2.3 The Design Process: Demonstrating Procedural Thinking

Engineering design thinking, according to the Atman et al. (2007), has ten steps: (1) defining the problem; (2) gathering the information; (3) generating the idea based on the information; (4) establishing a model according to our idea; (5) analyzing whether the model is feasible; (6) evaluation; (7) making decision; (8) communicating the solution; (9) implementing the solution; (10) redesigning. In this process, the teaching objectives aim to guide students to build models of the project, analyze whether the projects are feasible and find the 'optimal' solution within their ability. The 'optimal' solution does not mean that the students need to find the best solution that could solve the real-world problem. This optimal solution means that the teacher should guide the students to adjust their program during the process of the formulating program. During the analysis step, teachers should guide students to confirm that the client's needs are met and to ensure that all team members understand the final solution. The above analysis also shows that there are certain differences between design thinking processes and problem-solving processes.

5.3 Enabling Constructive Thinking in Building Products

Human beings develop, produce, process, and build existing material materials and living environments systematically to realize their needs, which is engineering (2017). And the core of engineering is construction (2017). Therefore, engineering thinking is essentially a kind of constructive thinking, which observes, analyzes, weighs, and deals with problems from the perspective of developing, producing, processing, and constructing artificial systems needed by human beings themselves, and constructive thinking is characterized by comprehensiveness, weighing, and rules. An effective way to develop constructive thinking.

5.3.1 Disciplinary integration: enhancing integrative thinking

STEM education activities are the process of applying knowledge from science, technology, engineering, math, art, social and other disciplines to solve real-world problems.

It is not simply a combination of knowledge from science, technology, engineering, mathematics, art, society, and other disciplines; it is the formation of a coherent and organized curriculum structure from these disciplines through practical engineering activities (Zhao, 2006). In solving real-world problems, various forms and methods of thinking need to be mobilized and used to solve problems from different perspectives, solutions, and paths based on knowledge from various disciplines and practical engineering experience. In this process, it involves the integrated application of knowledge of science, technology, engineering, mathematics, art, society, and other disciplines, just like a rose, science, technology, engineering, mathematics, art, and society are the petals of the rose, which are cross-compounded, and the construction products are the receptacles and branches that support the petals (Mark & Hollenstein, 2017). The petals of the rose are not simply stacked but are cross-compounded, and this integration is precisely what synthesizes the strengths of each discipline so that the knowledge of science, technology, engineering, mathematics, art, and society complement and contribute to each other. In this way, STEM education activities can more effectively develop students' integrated problem-solving skills and promote the development of their integrative thinking.

5.3.2 Integrated optimization: developing a trade-off mindset

There is no absolute best solution in engineering, only a relatively better solution for a given time, a given place, and a given environment. Balancing various factors in a complex situation and choosing a relatively better solution is trade-off thinking in engineering. Engineering practice requires balancing the needs of technology, stability, cost, durability, safety, ethics, etc. For example, students are asked to design and build a rock-throwing machine with a total evaluation score of 100 points, of which 25 points each are for throwing distance, throwing accuracy, stability, and cost, and one vote is counted as 0 points if the product has safety issues. When students are designing and producing products, they have to consider all the above elements, optimally choose various options, reconcile various needs, make complex trade-offs, compromises, and coordination of various needs, and produce the product they are most satisfied with. For example, a rock thrower may throw far but not accurately, or it may throw accurately but not far enough, so the student has to weigh the technical needs; when testing, one rock thrower occasionally throws far and accurately, but in most cases fails to meet the requirements, while another rock thrower, which does not throw far, is stable and achieves approximately the same result every time, so the student has to weigh the stability needs; the rock thrower throws farther, more accurate, and more stable, but the materials used are expensive and cost too much, at which point the student has to weigh the cost needs. Because safety is a veto, safety is an issue that students have to consider. Students develop trade-off thinking in this practice of constant trade-offs and compromises for integration and optimization.

5.3.3 Setting standards: reinforcing rule-based thinking

In STEM learning activities, teachers and students develop rules based on product requirements. This requires students to think and make products according to these rules so that students' thinking and actions are rule-based and predictable, which is rule-based thinking in engineering (Li, 2015). Assessment rules in STEM learning activities are multiple and can be assessed in terms of safety of use, reliability of the product, price, and visual aesthetics, in addition to considering whether students' work achieves the intended function. Students complete the design and production of products according to the rules of assessment in STEM learning activities; it ensures that the design and production of products are followed and that the accomplishment of goals becomes predictable. Therefore, following the rules and thinking and making products according to their needs becomes an important feature and inherent requirement of engineering thinking.

STEM education is problem-solving, engineering design, and building product-based learning that is interdisciplinary and open-ended (Wu, 2018). Ineffective STEM education, the goal of developing engineering thinking can be achieved.

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