THE DEVELOPMENT AND EVALUATION OF ENGINEERING DESIGN PROCESS STEM MODULE TO CULTIVATE ENGINEERING THINKING AND ENGINEERING CAREER INTEREST OF EIGHTH-GRADE MIDDLE SCHOOL STUDENTS

XUE XIANGYING

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by

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LIST OF SYMBOLS

Box's M	Box's M Test of Equality of Covariance Matrices
H_0	Null Hypothesis
KR-20	Kuder and Richardson Formula
N	Number
p	Probability value
x^2	Chi-square distribution
α	Cronbach's Alpha

LIST OF ABBREVIATIONS

ADDIE	Analysis, Design, Development, Implementation and Evaluation
ANOVA	Analysis of Variance
ASSURE	Analyze, State, Select, Utilize, Require and Evaluate
CG	Control Group
CIS	Career Interest Survey
CVI	Content Validity Index
ECI	Engineering Career Interest
ECIS	Engineering Career Interest Survey
EDMT	Engineering Decision-making Thinking
EDP	Engineering Design Process
EDP-STEM	STEM based on Engineering Design Process
EDT	Engineering Design Thinking
EET	Engineering Evaluation Thinking
EG	Experimental Group
EIT	Engineering Implementation Thinking
EOT	Engineering Optimization Thinking
ETSAQ	Engineering Thinking Self-Assessment Questionnaire
ETTP	Engineering Thinking Test Paper
I-CVI	Item Content Validity Index
JEPeM-USM	Jawatankuasa Etika Penelidikan Manusia Universiti Sains Malaysia
K-12	Kindergarten through 12th Grade
MANOVA	Multivariate Analysis of Variance
RQ	Research Question
SCCT	Social Cognitive Career Theory
S-CVI	Scale Content Validity Index
SPSS	Statistical Package for the Social Science
STEM	Science, Technology, Engineering and Mathematic
STEAM	Science, Technology, Engineering, Art and Mathematic
USM	Universiti Sains Malaysia

LIST OF APPENDICES

PEMBANGUNAN DAN PENILAIAN MODUL PROSES REKA BENTUK KEJURUTERAAN STEM UNTUK MEMUPUK PEMIKIRAN KEJURUTERAAN DAN MINAT KERJAYA KEJURUTERAAN MURID GRED LAPAN SEKOLAH MENENGAH

ABSTRAK

Kajian ini bertujuan untuk membangunkan modul pembelajaran STEM berasaskan Proses Reka Bentuk Kejuruteraan (modul EDP-STEM) dan menilai keberkesanannya dalam memupuk dan mengekalkan pemikiran kejuruteraan murid Gred Lapan (termasuk pemikiran pembuatan keputusan kejuruteraan, pemikiran reka bentuk kejuruteraan, pemikiran pelaksanaan kejuruteraan, pemikiran penilaian kejuruteraan, dan pemikiran pengoptimuman kejuruteraan) serta minat kerjaya dalam kejuruteraan. Modul EDP-STEM, berdasarkan teori pembelajaran situasional, teori konstruktivisme, dan teori kerjaya kognitif sosial, dibangunkan menggunakan model reka bentuk pengajaran ADDIE dan merangkumi tiga topik sains: “Pemindahan Haba”, “Mekanik”, dan “Keapungan”. Selepas pembangunan, kesahan dan kebolehpercayaan modul disahkan (S-CVI = 0.925, koefisien α = 0.804), memastikan modul ini dibangunkan dengan baik. Kajian ini menggunakan reka bentuk kuasi-eksperimen kumpulan tidak setara dengan ujian pra-ujian dan pasca-ujian melibatkan 60 murid Gred Lapan. Kumpulan eksperimen (N=30) menggunakan modul EDP-STEM, manakala kumpulan kawalan (N=30) menerima pendidikan STEM konvensional. Tiga instrumen penyelidikan digunakan: Kertas Ujian Pemikiran Kejuruteraan, Kuisian Penilaian Diri Pemikiran Kejuruteraan, dan Kaji Selidik Minat Kerjaya Kejuruteraan. Instrumen ini digunakan pada kedua-dua kumpulan dalam ujian pra-ujian, pasca-ujian, dan ujian pasca-ujian lanjutan. Data kualitatif yang dikumpulkan semasa

pembangunan modul dianalisis secara tematik, manakala data kuantitatif dianalisis menggunakan kaedah deskriptif dan inferensi. Keputusan MANOVA satu hala menunjukkan perbezaan ketara dalam lima pemboleh ubah pemikiran kejuruteraan antara skor pasca-ujian kumpulan eksperimen dan kawalan ($F (5,54) = 14.508$, $p < 0.05$; Wilks' Lambda = 0.427; partial eta squared = 0.573). Keputusan ANOVA satu hala bagi setiap pemboleh ubah juga menunjukkan penemuan ketara ($p < 0.01$). MANOVA pengukuran berulang menunjukkan kesan ketara merentasi tiga masa ujian untuk kedua-dua kumpulan (Wilks' Lambda = 0.417, $F (10,224) = 12.301$, $p < 0.05$, partial eta squared = 0.354). Perbandingan berpasangan untuk interaksi Masa × Kumpulan juga menunjukkan perbezaan ketara ($p < 0.01$), menunjukkan perbezaan ketara dalam lima pemboleh ubah pemikiran kejuruteraan antara kumpulan eksperimen dan kawalan dalam ujian pasca-ujian tertunda. Ujian-t sampel bebas menunjukkan perbezaan ketara dalam skor pasca-ujian minat kerjaya kejuruteraan antara kumpulan ($p < 0.05$). ANOVA pengukuran berulang menunjukkan kesan ketara dalam minat kerjaya kejuruteraan merentasi masa ujian dalam ujian pasca-ujian tertunda (Wilks' Lambda = 0.612, $F (2,57) = 18.045$, $p < 0.05$, partial eta squared = 0.388). Perbandingan berpasangan untuk interaksi Masa × Kumpulan juga menunjukkan perbezaan ketara dalam minat kerjaya kejuruteraan antara kumpulan dalam ujian pasca-ujian tertunda ($p < 0.05$). Secara keseluruhannya, keputusan menunjukkan bahawa modul EDP-STEM berkesan dalam memupuk dan mengekalkan pemikiran kejuruteraan dan minat kerjaya kejuruteraan murid Gred Lapan. Modul EDP-STEM menunjukkan potensi kurikulum STEM yang berstruktur, berasaskan amali, dan disokong oleh teori dalam memupuk kemahiran kognitif dan pemikiran yang penting, di samping membentuk persepsi serta motivasi murid terhadap laluan kerjaya yang berkaitan dengan kejuruteraan. Implikasi kajian ini memberikan panduan praktikal kepada pereka bentuk kurikulum, pendidik STEM, dan pembuat dasar dalam usaha meningkatkan hasil pembelajaran STEM di peringkat pendidikan menengah.

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ABSTRACT

This study developed a STEM learning module based on the engineering design process (EDP-STEM module) and evaluated its effectiveness in cultivating and retaining eighth-grade students' engineering thinking (engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking and engineering optimization thinking) and engineering career interest. The EDP-STEM module, based on situational learning theory, constructionism theory, and social cognitive career theory was developed using the ADDIE instructional design model and covers three scientific topics: "Heat Transfer", "Mechanics", and "Buoyancy". After development, the module's validity and reliability were verified (S-CVI = 0.925, α coefficient = 0.804), ensuring that it was well-developed. The study employed a non-equivalent groups pretest-posttest quasi-experimental design with 60 eighth-grade students participating. The experimental group (N=30) used the EDP-STEM module, while the control group (N=30) received conventional STEM education. Three research instruments were used: the Engineering Thinking Test Paper, the Engineering Thinking Self-Assessment Questionnaire, and the Engineering Career Interest Survey. These instruments were administered to both groups in pre-tests, post-tests, and delayed post-tests. Qualitative data collected during module development were thematically analyzed, while quantitative data were analyzed using descriptive and inferential methods. One-way

MANOVA results showed significant differences in the five engineering thinking variables between the post-test scores of the experimental and control groups ($F (5,54) = 14.508$, $p < 0.05$; Wilks' Lambda = 0.427; partial eta squared = 0.573). Subsequent one-way ANOVA results for each variable also showed significant findings ($p < 0.01$). Repeated measures MANOVA indicated significant effects across the three test times for both groups (Wilks' Lambda = 0.417, $F (10,224) = 12.301$, $p < 0.05$, partial eta squared = 0.354). Pairwise comparisons for the Time*Group interaction also showed significant differences ($p < 0.01$), indicating significant differences in the five engineering thinking variables between the experimental and control groups in the delayed post-test. Independent samples t-tests revealed significant differences in post-test scores of engineering career interest between the groups ($p < 0.05$). Repeated measures ANOVA showed significant effects in engineering career interest across the test times (Wilks' Lambda = 0.612, $F (2,57) = 18.045$, $p < 0.05$, partial eta squared = 0.388). Pairwise comparisons for the Time*Group interaction also indicated significant differences in engineering career interest between the groups in the delayed post-test ($p < 0.05$). Overall, the results indicate that the EDP-STEM module effectively cultivates and retains eighth-grade students' engineering thinking and engineering career interest. The EDP-STEM module demonstrates the potential of structured, hands-on, and theory-informed STEM curricula to cultivate essential cognitive and thinking skills, while also shaping students' perceptions and motivations toward engineering-related career pathways. These implications provide practical guidance for curriculum designers, STEM educators, and policymakers seeking to enhance STEM learning outcomes at the secondary education level.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The term “STEM” originated in the United States. In 1986, the National Science Commission published “Undergraduate Education in Science, Mathematics, and Engineering” (National Science Board, 1987). This document first abbreviated the four disciplines of Science, Mathematics, Engineering, and Technology as SME&T. In 2001, SME&T education was renamed STEM education. Since then, STEM education has grown to be a significant part of the American education system (McComas & Burgin, 2020). As a proper noun, STEM means that it is not a simple superposition of four disciplines, but an organic integration of four disciplines (Labov & Olson, 2014). However, the study has found that within the whole of STEM education, only “engineering education lacks a strong tradition in K-12 education” (Moore et al., 2021). Bybee highlighted that educators frequently overlook technical and engineering education within STEM education (Bybee, 2010). In the history of primary and secondary education, the “E” in STEM education has been largely overlooked (National Research Council, 2010).

In 2009, the National Research Council of the United States published the “K-12 Engineering Education Standards” to address the absence of engineering education within K–12 STEM curricula. This report delineated three fundamental principles of engineering education: cultivating engineering thinking habits, bolstering STEM knowledge and skills, and emphasizing engineering design (National Research Council, 2009). Engineering design stands as a crucial element in engineering education, essential for students aiming to pursue STEM disciplines (Atman et al., 2011; Lin et al., 2021). Many countries promote STEM-based engineering curricula in

K-12 education (Chien & Chu, 2018; Cruz et al., 2021) due to the growing significance of engineering design experiences in students' STEM education and career readiness in recent years (Crismond & Adams, 2012). Research in K-12 education has demonstrated that technology learning activities centered on engineering design enhance STEM education (Lin et al., 2021).

"The Framework for K-12 Science Education" in the United States recommended that integrating the engineering design process as a context or instructional approach effectively enhances the integration of STEM disciplines among students (Engineering, 2010). Indeed, within STEM, "engineering" serves as a pivotal "bridge" that connects science, mathematics, and technology. It enables students to apply scientific, mathematical, and technical knowledge to design, optimize project solutions, and complete engineering tasks. Additionally, it enhances students' abilities in engineering thinking, problem-solving, collaboration, creativity, and other advanced skills (Shi & Li, 2019). During the engineering design process, students have the opportunity to integrate abstract knowledge from various disciplines, fostering increased interest and deeper comprehension of subject matter. Engineering programs facilitate the integration of STEM knowledge among students by enabling them to engage in engineering design, practice engineering skills, and develop production capabilities (Bybee, 2010; Kelley et al., 2010). STEM-centered engineering design activities establish connections between theoretical concepts and practical applications, fostering students' intrinsic motivation to learn and promoting their interest in and integration of STEM disciplines (Kwon et al., 2021).

Research indicated that the majority of Chinese middle school students lack the understanding and awareness of engineering education, resulting in low interest in engineering careers and low identification with the engineering career (Huang, 2019).

Some reasons may be related to culture, social background and other factors. Studies indicated that students begin formulating career decisions as early as middle school, and these aspirations are crucial predictors of their choices in STEM majors during their academic journey (Loon, 2021). As early as 2020, a study found that Chinese middle school students also have differences in engineering thinking compared with their peers in the United States and New Zealand, manifested in vague understanding of engineering thinking, cognitive confusion, inaccurate self-evaluation, and other problems, and this situation has persisted to the present day (Shi & Li, 2020).

At present, in the middle school stage, China does not divide engineering into a separate subject, and the learning of engineering knowledge is often hidden in other courses, such as science, physics, biology and chemistry. Students believed that it is difficult for them to truly experience the fun and sense of accomplishment of engineering practice in this class, which leads to their low interest in engineering education and lack of engineering thinking ability (Zhu, 2015). The National Research Council has advocated that integrated STEM can enhance learners' educational experiences and enrich their learning processes (Kelley & Knowles, 2016; National Research Council, 2013). The main reason is that the learning process determines the academic achievement of the learners, such as the interest to pursue advanced studies in one's favorite field, and to pursue the field of interest in a career in a related field (Freeman et al., 2019).

Although the Ministry of Education of China has released "the Implementation Plan for STEM Education in Primary and Secondary Schools (2018-2020)", recognizing that integrating the engineering design process into STEM education could address these issues, there remains a research gap regarding the effective integration of the engineering design process with STEM education. In 2021, the

Chinese Academy of Engineering published the report titled "Suggestions on STEM Education to Promote Future Talent Training", highlighting the deficiency in teaching and curriculum resources related to the engineering design process in China's current STEM education framework. The report emphasized the necessity for research and development in this area to address the existing gaps.

1.2 Background of Studies

According to the 2018 China Science and Technology Talent Development Report and the data of the Academic Degrees Committee of the State Council, the total number of STEM talents in China needs to reach 65 million, but at present it is less than 50 million, which is closely related to the current problems in China's engineering education (Gao, 2020). For example, the uneven level of engineering education in China, the very few opportunities for students to participate in engineering practice, the serious lack of engineering practical experience among teachers, the low interest of students in engineering careers, and the lack of training in engineering thinking have all limited the development of engineering and technical talents (Xu et al., 2023).

In the latest 2018 PISA test, Chinese students achieved an average score of 591 in mathematics and 590 in science, with an average score of 555 in reading (Candido et al., 2020). Despite Chinese students excelling in PISA assessments, the 2019 Trends in International Mathematics and Science Study (TIMSS) indicated that their performance in "applied problems" lags behind that of peers from other nations (Chen & Bai, 2019). This result indirectly showed that Chinese students need to better develop engineering thinking, because "applied questions" are not only a method to test students' mastery of knowledge, but also a mean to examine students' thinking process and ability. Several scholars have posited a strong correlation between applied problems and engineering thinking (Hynes et al., 2016). Engineering thinking prioritizes decision-making, design, implementation, evaluation, and optimization processes. These processes have many similarities with the problem-solving process in application problems (National Research Council, 2014). This also indirectly suggested that Chinese students may have certain deficiencies in engineering thinking.

The practice and promotion of STEM education can help countries improve the quantity and quality of high-quality talents, promote technological innovation and industrial upgrading, and improve the comprehensive strength of the country (Hu, 2018). According to the Global Innovation Index (GII) ranking released in 2021, China ranked only 12th, far lower than other countries (Jewell, 2021). This showed that China's STEM education needs further development to improve students' STEM academic achievements to promote national innovation and competitiveness. Within STEM education, engineering education holds significant importance, as it effectively nurtures students' practical and innovative skills (Yalçın & Erden, 2021). Engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking and engineering optimization thinking are important components of engineering education (Wang, 2018). The cultivation of these thinking abilities helped students master the methods and processes of engineering design, enhanced their interest in engineering careers, and made up for the lack of Chinese engineering talents.

Numerous studies have demonstrated that integrating the engineering design process into STEM education can greatly enhance students' proficiency in STEM disciplines and their engineering thinking capabilities (Bybee, 2010). The National Council of Engineering and Technology Education (NCETE) recommended incorporating engineering design challenge modules into integrated STEM courses, positing that students could cultivate engineering thinking through engaging in these engineering design challenges (Householder et al., 2012). The middle school stage is the key period for teenagers to contact engineering education and improve their interest in engineering. The career interests of middle school students have great predictive power for their future work in this field (Wang et al., 2020). All of these studies suggested that integrating integrated STEM education into the engineering design process may provide a viable solution for addressing the lack of engineering thinking and engineering career interest among middle school students in China.

Despite the Chinese Ministry of Education issuing the “Several Opinions of the Ministry of Education on Accelerating the Implementation of STEM Education in Primary and Secondary Schools” at the National Education Conference, which emphasized the importance of incorporating the engineering design process into integrated STEM education to enhance students’ engineering practice skills and literacy, China remains in the nascent stages of embedding the engineering design process within STEM education (Zhang, 2019). Although the Chinese government has been promoting education reform, the pace of reform has been relatively slow, and neither STEM education nor engineering education has been formally integrated into the primary and secondary school curricula. At present, most public schools in China primarily emphasize science education. However, the abstract nature of some scientific concepts presents ongoing challenges in both teaching and learning these subjects. For example, in topics such as “Heat Transfer”, “Mechanics” and “Buoyancy”, students often lack sufficient life experience and integrated knowledge to apply their understanding to real-world situations and solve practical problems (Liang et al., 2017; Zhou, 2017; Zou et al., 2022). Much of the reason for this phenomenon lies in traditional teaching, which is characterized by rote memorization of rules and formulas (Bloom et al., 1956; Rivet & Krajcik, 2012).

Building on the aforementioned discussion, this study focused on the topics of "Heat Transfer", "Mechanics" and "Buoyancy" within the science discipline. It integrated the engineering design process with STEM education to develop an EDP-STEM module aimed at cultivating engineering thinking and engineering career interest among eighth-grade middle school students.

1.3 Problem Statements

In the context of rapidly advancing technology and globalization, cultivating students' engineering thinking has become a key educational objective, aimed at helping students address complex real-world problems and driving innovation and technological progress (English, 2016; Wang & Zhang, 2019). Engineering thinking is not merely a knowledge system within a specific discipline; it encompasses a multifaceted thinking process, including engineering decision-making, design, implementation, evaluation, and optimization. It is a core competence for students to solve practical problems and engage in innovative design (Gu, 2013; Chen, 2020). Increasing research indicated that engineering thinking is not only crucial for technological development but also one of the core competencies students' needs in the 21st century (Chiang et al., 2022; Naukkarinen et al., 2023). As technology evolves rapidly, many countries around the world have recognized that fostering students with innovative and problem-solving abilities will support national future competitiveness (Chen, 2020; Li, 2020). Therefore, how to effectively cultivate students' engineering thinking during the basic education stage has become a significant issue in the educational field.

STEM education in China's secondary schools faces numerous challenges during its implementation. Traditional teaching methods overly focus on the transmission of subject-specific knowledge, neglecting the development of students' interdisciplinary problem-solving skills. This limitation results in students' inability to apply what they have learned to real-world problem solving (Topalli & Cagiltay, 2018). While some schools have begun attempting to integrate STEM education into the classroom, the curriculum content is still often disconnected from real engineering problems and lacks effective integration of knowledge across disciplines. As a result, students fail to develop systematic and creative thinking when tackling complex engineering tasks (Zhan et al., 2023). This educational model restricts the development of students' engineering thinking and further affects their interest in and identification with engineering careers. Therefore, incorporating the Engineering Design Process (EDP) into STEM education can not only foster interdisciplinary knowledge application but also effectively cultivate students' engineering thinking, helping them solve real engineering problems (Liu & Chiang, 2020).

Research indicated that Chinese students exhibit deficiencies in engineering thinking. For example, Zhou et al. (2020) put forward that Chinese middle school students have weak engineering decision-making thinking and engineering design thinking ability. They believed that engineering design thinking can provide strong strategic support for students in solving problems. Han's study indicated that middle school students in Jiangxi Province demonstrated weak engineering decision-making skills, with average scores of 2.8 for multi-faceted problem analysis and 2.6 for logical activity planning (on a 5-point scale). Similarly, their scores in experimental inquiry (2.9) and hands-on skills (2.7) reflected underdeveloped engineering design thinking (Han, 2021). As a systematic problem-solving mode, EDP can provide scaffolding for students' engineering design, so that students can refer to the engineering design process and clearly carry out team STEM activities (Zhou et al., 2020). Li (2022) pointed out that the current Chinese students' engineering design thinking is weak, which is mainly manifested in the lack of systematic and creative consideration in the design process, and the lack of ability to compare and analyze different schemes (Li, 2022). Liao (2018) pointed out that Chinese students' engineering implementation thinking ability has certain deficiencies, mainly manifested in their lack of practical operation ability and their inability to really deal with practical problems (Liao, 2018). Wang (2016) believed that Chinese students' engineering evaluation thinking and engineering optimization thinking are relatively weak, mainly manifested in a lack of comparison and analysis of different schemes in the design and implementation process, as well as the ability to optimize design, and a lack of reflection and summary ability on engineering achievements (Wang, 2016).

However, engineering thinking is difficult to cultivate in traditional education. The reason is that Chinese traditional education divides courses according to specific subjects, and the divided teaching stays at the level of students passively accepting learning, and students cannot actively solve complex problems (Topalli & Cagiltay, 2018). In China's basic education stage, the cultivation of engineering thinking is neither explicitly included in curriculum objectives nor incorporated into teaching practices as a defined instructional goal (Zhan et al., 2023). Research has revealed that the development of engineering thinking within the Chinese education system is often implicitly embedded in robotics (Yan et al., 2013) and general technology classes (Fu, 2020), with students cultivating engineering thinking autonomously (Chiang et al., 2022). Due to the lack of accurate teaching objectives and evaluation methods, the training results are also unsatisfactory. In addition, most of these courses are aimed at undergraduates, high school students, and fewer elementary and middle school students. However, in the middle school stage, the self-consciousness of teenagers' thinking activities increases, the reflection and monitoring of thinking are significantly improved, and the creativity of thinking is developing rapidly (Li, 2018), which is the best time to cultivate engineering thinking. Secondly, most of these courses focus on teaching examination-oriented knowledge such as robots and general technology, and students finally only acquire the knowledge needed to cope with the exam, ignoring the cultivation of other thinking abilities. This current situation limits the effective integration between various disciplines, ultimately leading to the cultivation of so-called engineering thinking being superficial, and engineering thinking losing its core value of solving practical problems through engineering design process (Liu & Chiang, 2020; Naukkarinen et al., 2023).

In addition to the lack of engineering thinking, students' interest in engineering careers also requires significant improvement. According to a survey by Huang (2019), only 24.75% of Chinese middle school students are interested in pursuing engineering careers, reflecting a low level of interest in engineering disciplines. By analyzing the reasons behind students' career choices, the researcher found that most students lacked understanding of the job responsibilities of engineers and senior engineers. Many students have little exposure to the term "engineering" in their daily classroom, family, and social lives (Huang, 2019). In a sense, the lack of educational concepts and policies in K-12 engineering education has resulted in a gap in basic knowledge about engineering among middle school students (Huang, 2019).

In fact, current science education for middle school students in China also faces numerous challenges. Firstly, there is an excessive emphasis on acquiring knowledge required for exams, neglecting the development of students' higher-order abilities

(Guo, 2012). Secondly, teachers tend to focus on imparting disciplinary knowledge and skills, with less emphasis on inquiry-based and contextualized teaching approaches (Zheng et al., 2023). Thirdly, there is a lack of development in teaching resources. A survey revealed that 79% of teachers and students believed that science textbooks do not adequately reflect the integration of multidisciplinary content, the interdisciplinarity between subjects, and the foundational nature of science. They failed to embody the comprehensive nature of the science curriculum (Xu et al., 2023). For example, challenging topics like “Heat Transfer”, “Mechanics”, and “Buoyancy” lack relevant hands-on experiments (Xie, 2017). The selection of “Heat Transfer,” “Mechanics,” and “Buoyancy” for integration into the Engineering Design Process (EDP) is supported by prior research highlighting their relevance to real-world engineering applications and suitability for middle school learners. Heat transfer has been effectively taught through engineering design challenges that promote conceptual understanding and correct misconceptions (Schnittka & Bell, 2011). Mechanics concepts, such as Newton’s laws, are central to motion and structural design problems, enabling students to apply theoretical knowledge to authentic tasks (Workosky, 2017). Buoyancy offers an accessible context for exploring fluid mechanics through hands-on projects like boat-building challenges (STEM Pre-Academy, 2015). Together, these topics provide age-appropriate, interdisciplinary content that aligns well with EDP and fosters students’ engineering thinking and problem-solving skills.

Although there have been studies to cultivate students’ engineering thinking through the courses of science-engineering integration (Song, 2019), intelligent robots (Wang, 2018) and general technology courses (Chen, 2020), the results have been slightly improved. However, due to the limitations of teaching stage, teaching cost, faculty capacity, and students’ cognitive level, the above approach is not suitable for promotion to the middle school stage. Some researchers attempt to incorporate the engineering design process into STEM education to address the aforementioned issues. However, according to the literature review, the majority of studies focus primarily on effectively cultivating students' engineering perspectives (Aydoğan & Çakıroğlu, 2022), interests in engineering disciplines (Ayar, 2015), engineering concepts (Lampley et al., 2022), as well as technological and engineering literacy (Chen, 2018; Zeng, 2020). There is limited research on the development of problem-solving skills, engineering design skills, and engineering thinking (Winarno et al., 2020). Furthermore, only a few studies have adopted an extended intervention period (e.g., 12 weeks) to examine both the cultivation and long-term retention of engineering career interest (Yoon et al., 2014; Dare et al., 2019). There is almost no research exploring whether and how STEM modules based on the engineering design process can cultivate engineering thinking and engineering career interest among eighth-grade middle school students in China. Consequently, there is an urgent need for STEM education to integrate the engineering design process to cultivate learners' engineering thinking and engineering career interest, thereby nurturing emerging engineering and technical talents to meet the challenges of the new century.

To address the above-mentioned problems, this study was divided into two parts. The first phase involves developing a STEM module based on the engineering design process, integrated with scientific topics, and subsequently evaluating the module. The second phase comprises an empirical study aimed at evaluating the effectiveness of the EDP-STEM module in cultivating and retaining engineering thinking (engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, engineering optimization thinking) as well as engineering career interest among eighth-grade middle school students.

1.4 Research Objectives

This study has two main objectives, involving the development and effectiveness evaluation of the EDP-STEM module. The objectives of this study are outlined as follows.

1.4.1 The First Objective

The first research objective is to develop a STEM learning module based on the engineering design process (EDP-STEM module) for eighth-grade middle school students. To accomplish this objective, a research sub-objective is included:

To develop a STEM module based on the engineering design process (EDP-STEM module) to promote the cultivation of engineering thinking (engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, engineering optimization thinking) and engineering career interest for eighth-grade middle school students.

1.4.2 The Second Objective

The second research objective of this study involves the evaluation of the EDP-STEM module, specifically evaluating its effectiveness in enhancing and retaining engineering thinking (engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, engineering optimization thinking) and engineering career interest among eighth-grade middle school students. The evaluation of the EDP-STEM module involves four sub-objectives:

2(a) To determine whether there are significant differences in the post-test scores of engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking between the experimental and control groups of eighth-grade middle school students.

2(b) To determine whether there are significant differences in the delayed post-test scores of engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking between the experimental and control groups of eighth-grade middle school students.

3(a) To determine whether there is a significant difference in the post-test scores of engineering career interest between the experimental and control groups of eighth-grade middle school students.

3(b) To determine whether there is a significant difference in the delayed post-test scores of engineering career interest between the experimental and control groups of eighth-grade middle school students.

1.5 Research Questions

The research questions of this study are aimed at achieving research objectives. The following research questions are outlined according to these objectives. The first research objective lists one research sub-objective; therefore, there is a corresponding research sub-question:

R1: How to develop a STEM module based on engineering design process (EDP-STEM module) to promote the cultivation of engineering thinking (engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking and engineering optimization thinking) and engineering career interest of eighth-grade middle school students?

To achieve the second research objective, involving four research sub-objectives, a total of four research sub-questions are included:

R2(a): Are there any significant differences in the post-test scores of engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking between the experimental and control groups of eighth-grade middle school students?

R2(b): Are there any significant differences in the delayed post-test scores of engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking between the experimental and control groups of eighth-grade middle school students?

R3(a): Is there any significant difference in the post-test scores of engineering career interest between the experimental and control groups of eighth-grade middle school students?

R3(b): Is there any significant difference in the delayed post-test scores of engineering career interest between the experimental and control groups of eighth-grade middle school students?

1.6 Research Hypothesis

Research question 1 does not involve testing null hypotheses as it focuses on the objectives, components, validity, and reliability of the EDP-STEM learning module. Therefore, this study only tested four null hypotheses, which are research questions 2(a), 2(b), 3(a) and 3(b). Based on the research questions of this study, the null hypotheses (H_0) are formed.

H_{01}: There are no significant differences between the post-test scores of eighth-grade middle school students in the experimental and control groups in engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking.

H_{02}: There are no significant differences between the delayed post-test scores of eighth-grade middle school students in the experimental and control groups in engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking.

H_{03}: There is no significant difference between the post-test scores of eighth-grade middle school students in the experimental and control groups in engineering career interest.

H_{04}: There is no significant difference between the delayed post-test scores of eighth-grade middle school students in the experimental and control groups in engineering career interest.

1.7 Significance of Studies

This research developed a STEM module based on the engineering design process (EDP-STEM module) and evaluated the cultivation effectiveness and retention effectiveness of engineering thinking (engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking and engineering optimization thinking) and engineering career interest of eighth-grade middle school students. The results of this study could benefit many stakeholders because it can be used as a reference source for integrating the engineering design process into STEM education to cultivate engineering thinking and engineering career interest in the future.

a. Teachers

The EDP-STEM module developed in this study provides a teaching guidebook for teachers. This guidebook not only provides teachers with ready-made instructional design resources, but also provides more new ideas for cultivating engineering thinking and engineering career interest. The three activities in this module all originate from real-life problems in China, providing teachers with connections between each activity and STEM disciplines. The instructional process aids teachers in comprehending the stages of the engineering design process and in cultivating students' engineering thinking and interest in engineering careers. In addition, this study selected the more challenging topic of "Heat Transfer" and "Mechanics" in eighth-grade science courses, among which "Mechanics" also includes the theme of "Buoyancy". In addition to assisting STEM teachers, it could also assist science teachers in teaching related content.

b. Students

The EDP-STEM module developed in this research is designed for students, providing them with various roles, such as engineering decision-makers, engineering designers, engineering constructors, engineering recorders and engineering evaluators, to help them experience the role of engineers and cultivate their interest in engineering careers. Throughout the learning process, students developed engineering thinking by participating in hands-on design and construction projects, as well as tackling engineering challenges. This process can enhance their comprehension and application of science, technology, mathematics, and engineering disciplines, enabling them to address real-world problems and develop essential 21st-century skills.

c. Ministry of Education

Currently, STEM education in China is deficient in resources for teaching and learning the engineering design process. The EDP-STEM module developed in this study addresses this gap by enhancing conventional STEM education with a focus on cultivating students' engineering thinking and engineering career interest. Additionally, it aims to enrich STEM teaching and learning resources for future integration of the engineering design process.

d. Other Researchers

Nowadays, many researchers in the field of STEM education in China are exploring effective ways to implement STEM education and engineering education in China, but few studies have integrated engineering design process into STEM education to cultivate students' engineering thinking and interest in engineering careers. The EDP-STEM module developed in this study could act as a stepping-stone for researchers to emphasize the importance of the engineering design process and introduce innovative approaches for cultivating students' engineering thinking and career interest in engineering.

1.8 Limitations of Studies

Although this study was carefully designed and implemented, certain limitations are anticipated due to the research scope, sampling strategy, and time constraints. These limitations may influence the generalizability and long-term validation of the findings. Acknowledging these limitations provides a clearer understanding of the study’s boundaries and helps inform future research directions.

First, the sample of this study consisted solely of eighth-grade students from a single public middle school in Anhui Province. As a result, the findings may not be generalizable to all middle schools across China. Students from different regions or private schools may exhibit diverse educational experiences or learning outcomes due to variations in teaching resources, socio-economic backgrounds, or school cultures.

Second, the research focused exclusively on Grade 8 students, and therefore the conclusions drawn may not be applicable to students at other educational stages, such as primary or senior secondary school. Differences in students’ developmental characteristics and learning readiness across grade levels may affect how they respond to the intervention.

Third, due to practical constraints such as limited time and resources, the empirical intervention was conducted over the course of only one semester. The short duration of the teaching period may have restricted the full development of students’ engineering thinking and engineering career interest. Although a delayed post-test was administered to assess the sustainability of the intervention’s effects, a longer implementation period would be required to evaluate its long-term impact more accurately.

1.9 Operational Definition

1.9.1 STEM Education

The term “STEM” first originated in the United States. In 1986, the National Science Council introduced the concept in their report “Science, Mathematics, and

Engineering Undergraduate Education" defining STEM education as an acronym for the four disciplines: science, mathematics, engineering, and technology (National Science Foundation, 1996). It aims to integrate fragmentary knowledge across multiple disciplines, including science, technology, engineering, mathematics, biology, physics, and art, to address real-world problems. The emphasis is on enhancing students' design capabilities and problem-solving skills.

This study incorporates the engineering design process within the framework of STEM education, integrating knowledge from science, technology, engineering, mathematics and other related subjects. It aims to cultivate students' engineering thinking and interest in engineering careers.

1.9.2 Engineering Design Process

The National Council for Engineering and Technology Education (NCETE) proposes a process model for engineering design challenges, which consists of 9 steps, which refer to identifying need or problem, researching need or problem, developing possible solution, selecting best possible solution, constructing a prototype, testing and evaluating solution, communicating the solution, redesigning, and completing decision (Householder et al., 2012).

This study developed a STEM module grounded in the engineering design process proposed by NCETE. Integrate the 9 steps with STEM activities to cultivate students' engineering thinking and engineering career interest.

1.9.3 The EDP-STEM Module

The EDP-STEM module is a learning module that focuses on scientific topics and specifically addresses the knowledge areas of "Heat Transfer", "Mechanics", and "Buoyancy". This module is not intended to improve students' knowledge required for exams, but rather to focus on cultivating their engineering thinking abilities and engineering career interest. The EDP-STEM module comprises of three activities, each corresponding to a specific knowledge area, totaling 12 lessons. The learning outcomes and objectives mentioned in this module regarding the science curriculum are derived from the People's Education Press textbooks and further developed through the integration of EDP and integrated STEM education. Each activity was designed based on the 9 steps of the EDP proposed by the National Center for Engineering and Technology Education (NCETE), with each step corresponding to the cultivation of engineering thinking. For example, the first and second steps of EDP aim to cultivate students' engineering decision-making thinking. Each activity in the module is based on real-world problems, namely "Save the Penguins", "Crossing the River", and "Lekima Rescue". In each activity, students were required to fill out an engineering recording sheet, where each student assumed different engineering roles, such as engineering decision-makers, engineering designers, engineering constructors, engineering recorders and engineering evaluators. This section aims to cultivate their interest in engineering careers.

1.9.4 Engineering Thinking

According to the process stages of engineering activities, Professor Gu Jianjun of Nanjing Normal University in China divided engineering thinking into engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking (Gu, 2009; Gu, 2010; Gu, 2013).

In this study, engineering thinking refers to a set of unique thinking modes and habits from reality formed in the process of engineering decision-making, engineering design, engineering implementation, engineering evaluation, and engineering optimization. Corresponding to the above engineering activities, engineering thinking in this study includes engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking. In this study, the researcher developed a paper-and-pencil test and a self-assessment questionnaire to evaluate engineering thinking, tailored to the cognitive level of eighth-grade middle school students. This assessment was informed by the engineering thinking evaluation scale designed by Professor Gu Jianjun of Nanjing Normal University (Gu, 2009; Gu, 2010; Gu, 2013). The Engineering Thinking Test Paper (ETTP) comprises 10 multiple-choice questions and 7 analytical questions, while the Engineering Thinking Self-Assessment Questionnaire (ETSAQ) includes 25 sub-items. The total scores for both instruments were normalized to a 50-point scale, with a maximum possible score of 100 points. Each of the five types of engineering thinking—engineering decision-making thinking, engineering design thinking, engineering implementation thinking, engineering evaluation thinking, and engineering optimization thinking—constituted 20% of the total score for each research instrument, resulting in a maximum score of 20 points for each type. In analyzing students' data across these dimensions, scores from both the ETTP and the ETSAQ are combined. This combined analysis is supported by the complementary nature of these assessment methods: the ETTP offers an objective evaluation of student performance based on teacher assessments, whereas the ETSAQ provides insights into students' self-awareness and internalization of their engineering thinking skills.

1.9.4(a) Engineering Decision-making Thinking

Engineering decision-making thinking refers to the thinking habit of systematically analyzing problems, assessing risks, weighing pros and cons, and formulating reasonable solutions in the context of real engineering problems, combined with existing knowledge and skills. It mainly includes two aspects, one is targeting decision-making, which refers to the strategic deployment of the project considering the whole. The second is path decision-making, which refers to formulating and choosing what kind of solution (Gu, 2009; Gu, 2010; Gu, 2013; Wang, 2009; Wang, 2014; Zhang, 2019).

In this study, engineering decision-making thinking is the thinking habit that students need to make systematic analysis, risk assessment, trade-off between advantages and disadvantages, and formulate reasonable plans for real problems according to the actual situation and their existing knowledge and skills. In this study, the researcher formulated test questions to evaluate engineering decision-making thinking, tailored to the cognitive level of eighth-grade middle school students. The self-assessment questionnaire for engineering decision-making thinking is adapted from the engineering thinking questionnaire developed by Professor Gu Jianjun's team at Nanjing Normal University and was developed using the Likert 5-level scale (Gu, 2009; Gu, 2010; Gu, 2013). This evaluation consists of three structures, which refer to the definition of engineering problems, the determination of engineering objectives, and engineering analysis.

1.9.4(b) Engineering Design Thinking

Engineering design thinking is a systematic and iterative cognitive process that generates solutions for the goals and challenges identified during the engineering decision-making phase. There may be different solutions during engineering design. At this time, under the guidance of engineering design thinking, the best solution should be considered (Gu, 2009; Gu, 2010; Gu, 2013; Wang, 2009; Wang, 2014; Zhang, 2019).

In this study, engineering design thinking is the thinking habit that students can make a series of engineering design plans or ideas based on real engineering problems, which can be specific problem solutions or specific engineering construction designs. In this study, the researcher designed test questions for engineering design thinking based on the cognitive level of eighth-grade middle school students. The self-assessment questionnaire for engineering design thinking is based on the engineering thinking questionnaire developed by Professor Gu Jianjun's team at Nanjing Normal University and was developed using the Likert 5-level scale (Gu, 2009; Gu, 2010; Gu, 2013). This evaluation consists of three structures, which refer to structural design, functional design, and engineering documentation.

1.9.4(c) Engineering Implementation Thinking

Engineering implementation thinking is a process of turning ideas into reality and gradually advancing the previous engineering blueprint. During the specific implementation process, there were many uncontrollable factors and unpredictable problems. It is essential to thoroughly evaluate the feasibility, inclusiveness, security, and privacy of the implementation, along with the value it provides to humanity (Gu, 2009; Gu, 2010; Gu, 2013; Wang, 2009; Wang, 2014; Zhang, 2019).

In this study, engineering implementation thinking is the thinking habit that students can perform visualization operations according to early engineering decisions and design schemes. In the STEM module, students should be able to select appropriate equipment for engineering construction and put it into specific engineering situations to solve engineering problems. In this study, the researcher developed test questions to assess engineering implementation thinking, tailored to the cognitive abilities of eighth-grade middle school students. The self-evaluation questionnaire for engineering implementation thinking is based on the engineering thinking