THE EFFECTS OF THE ENGINEERING DESIGN-BASED STEM MODULE IN ENHANCING CONCEPTUAL UNDERSTANDING OF FORCE AND MOTION AND MOTIVATION OF PRIMARY SCHOOL STEM LEARNING IN CHINA

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by

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LIST OF ABBREVIATIONS

ADDIE	Analysis, Design, Develop, Implement, Evaluate
C-G	Control Group
CUFM	Conceptual Understanding of Force and Motion
CUF	Conceptual Understanding of Force
CUM	Conceptual Understanding of Motion
CUNFLM	Conceptual Understanding of Newton's First Law of Motion
CVI	Content Validity Index
EDB-STEM	Engineering Design-based STEM
EDP	Engineering Design Process
E-G	Experimental Group
EiE	Engineering is Elementary
FAST	Five-hundred-meter Aperture Spherical Telescope
I-CVI	Item-level Content Validity Index
KR-21	Richardson Formula 21
LG	STEM Learning Goals
LIV	STEM Learning Interest Value
LS	STEM Learning Strategy
MANCOVA	Multiple Analysis of Covariance
MOE	Ministry of Education
MoL	Motivation of STEM Learning
MUSIC	Empowerment, Usefulness, Success, Interest, Caring
NAE	National Academy of Engineering
NASA	The National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NGSS	Next Generation Science Standards
NIES	National Institute of Education Sciences
NRC	National Research Council
OECD	Organisation for Economic Co-operation and Development
PISA	Programme for International Student Assessment
PLE	Perception of STEM Learning Environment

PSTDR	Primary Science Teaching Design and Reflection series
RQ	Research Question
RM MANCOVA	Repeated Measure Multiple Analysis of Covariance
SCSCE	Science Curriculum Standard of Compulsory Education
SE	Self-efficacy for STEM Learning
SPSS	Statistical Package for the Social Sciences
SRL	Self-regulated Learning
STEM	Science, Technology, Engineering, Mathematics
STS	Science, Technology, Society
STSE	Science, Technology, Society, Environment
US	United States
USM	Universiti Sains Malaysia
ZIPCP	Zhejiang-Indiana Parallel Classroom Project
3-D	Three-dimensional

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KESAN MODUL STEM BERASASKAN REKA BENTUK KEJURUTERAAN DALAM MENINGKATKAN KEFAHAMAN KONSEPTUAL BERKAITAN DAYA DAN GERAKAN SERTA MOTIVASI PEMBELAJARAN STEM SEKOLAH RENDAH DI CHINA

ABSTRAK

Pendidikan STEM peringkat rendah di China masih menghadapi cabaran dalam meningkatkan kefahaman konseptual dan mengekalkan motivasi pembelajaran pelajar. Untuk menangani isu ini, Kajian ini telah membangunkan satu modul STEM berasaskan reka bentuk kejuruteraan (EDB-STEM) untuk murid tahun tiga dan menilai kesannya terhadap pemahaman konsep Daya dan Gerakan serta motivasi mereka terhadap pembelajaran STEM. Modul EDB-STEM yang mengintegrasikan reka bentuk kejuruteraan dalam pembelajaran konsep Daya dan Gerakan dibangun dengan menggunakan Model ADDIE dan disokong oleh teori pembelajaran konstruktivis, teori nilai jangkaan, teori pembelajaran situasi, dan teori pembelajaran kendiri. Kajian kuasi-eksperimen (n = 82) membandingkan pendekatan EDB-STEM dengan pengajaran inkuiri tradisional. Data dikumpul melalui ujian pra, pasca dan pasca tertunda menggunakan Ujian Kefahaman Konsep Daya dan Gerakan serta Soal Selidik Motivasi Pembelajaran STEM. Analisis menggunakan ujian-t sampel berpasangan menunjukkan peningkatan signifikan dalam skor kumpulan eksperimen. Keputusan MANCOVA membuktikan kumpulan EDB-STEM mengatasi kumpulan kawalan dalam kedua-dua kefahaman konseptual dan motivasi pembelajaran STEM. Tambahan pula, analisis MANCOVA ukuran berulang menunjukkan modul ini mengekalkan kefahaman konseptual serta motivasi pembelajaran dengan lebih baik selepas empat minggu. Oleh itu, secara umumnya dapat disimpulkan bahawa integrasi reka bentuk

kejuruteraan ke dalam kurikulum sains sekolah rendah membantu meningkatkan pemahaman konsep Daya dan Gerakan serta motivasi pembelajaran STEM murid dan memainkan peranan penting dalam mempromosikan pendidikan STEM di China. Kajian ini menyumbang kepada penemuan tentang cara membangunkan modul STEM yang mengintegrasikan reka bentuk kejuruteraan dalam pembelajaran konsep Daya dan Gerakan yang lebih berkesan yang boleh dijadikan rujukan oleh guru untuk membangunkan modul yang sama bagi konsep-konsep atau topik-topik sains yang lain.

THE EFFECTS OF THE ENGINEERING DESIGN-BASED STEM MODULE IN ENHANCING CONCEPTUAL UNDERSTANDING OF FORCE AND MOTION AND MOTIVATION OF PRIMARY SCHOOL STEM LEARNING IN CHINA

ABSTRACT

Primary STEM education in China faces persistent challenges in developing students' conceptual understanding and sustaining their learning motivation. To address these issues, this study developed and evaluated an Engineering Design-Based STEM (EDB-STEM) module for third-grade students, focusing on Force and Motion concepts. The EDB-STEM module was developed using the ADDIE Model, incorporating engineering design principles and supported by multiple learning theories including constructivism, expectancy-value theory, situated learning, and self-directed learning. A quasi-experimental design (n=82) compared the EDB-STEM approach with school-adopted inquiry-based instruction. Data were collected through pre-tests, post-tests, and delayed post-tests using the Conceptual Understanding of Force and Motion Achievement Test and the Motivation of STEM Learning Questionnaire. Analysis using paired samples t-tests revealed significant improvements in the experimental group's scores. MANCOVA results demonstrated that the EDB-STEM group outperformed the control group in both conceptual understanding and motivation of STEM learning. Furthermore, repeated measures MANCOVA indicated it had better retention of conceptual knowledge and motivation four weeks after instruction. Therefore, in general, it can be concluded that integrating engineering design into the primary school science curriculum helps improve students'

conceptual understanding of Force and Motion, and their motivation of STEM learning, playing a crucial role in promoting STEM education in China. This study contributes to the findings on how to develop a more effective STEM module that integrates engineering design into the learning of Force and Motion concepts, which can serve as a reference for teachers to develop similar modules for other science concepts or topics for more effective performance.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The past decade saw the need to promote K-12 education, especially in science, technology, engineering and mathematics education (namely STEM education), has emerged as a consensus worldwide (Bybee, 2010; Anderson, 2020). To advance STEM education, integrating engineering into school disciplines in primary and secondary education has become a hot topic in policy documents, like *Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013), *Curricular Standards of Science in Elementary Schools* (Ministry of Education of the People's Republic of China [MOE (China)], 2017), which integrates contents related to technology and engineering into China's science curriculum.

Research on engineering in science and mathematics education has a relatively short history (Arık & Topçu, 2022), however, it has been widely suggested that integrating engineering and technology design into science and/or mathematics instruction—particularly through authentic, culturally and socially relevant problem-solving—can be an effective approach to advancing STEM education (Anwar et al., 2022; Bryan et al., 2015). Consequently, a significant body of research on STEM education has focused on engineering design (e.g., Guzey et al., 2014; Shi & Li, 2019), as it is considered a valuable pedagogical strategy for fostering interdisciplinary learning, as Moore et al. (2014) said,

Engineering contexts as spaces for students to develop real-world representations can be the catalyst for developing related scientific and mathematical concepts…

Apparently, integrating engineering design into science education practice is now both timely and necessary.

It’s widely expected that our future leaders, neighbours, and workers could understand and solve complex challenges of today and tomorrow from science and technology, and to meet demands of the dynamic and evolving workforce. Researchers frequently emphasized that getting a good conceptual understanding of force and motion is relevant to students’ lives (Harlen, 2010; OEDC, 2019) and for them to engage in STEM-related issues. Clearly, understanding and applying STEM disciplines knowledge is an inseparable step to achieve that hope (Bybee, 2010; Zollman, 2012; Falloon et al., 2020; Fan & Yu, 2017). STEM education, which emphasises the integration between disciplines (Zhong et al., 2022) to cultivate scientific and technological talents, could provide students authentic learning contexts in which they can make sense of STEM concepts and figure out connections among STEM disciplines. Thus, improving students’ conceptual understanding of force and motion should be the fundamental purpose of the high-quality STEM education. As another purpose of STEM education (NRC, 2014), improving students’ motivation of STEM learning would also be of benefit to students’ learning outcomes or interest towards STEM (Vennix et al., 2018). Data from several sources have identified various benefits of engineering design-based STEM education for K-12 students (e.g., Anwar et al., 2022). In particular, engineering design has been highlighted as an effective way to enhance primary student’s understanding of concepts and has positive effects on science learning motivation on students (Stammes et al., 2022; Marulcu, 2014; King & English, 2016; English et al., 2017; Delen & Yuksel, 2022).

In China, some scholars have recognized the potential of engineering design in STEM education, with mostly research focusing on strategies for developing engineering design-based STEM programs for primary schools (e.g., Dong, 2017; Xu, 2019). However, not enough attentions have been paid to integrating engineering with science education. Empirical studies investigating the impact of engineering design on Chinese primary students' conceptual understanding and motivation in science remain limited (Zhong et al., 2022). Futhermore, studies that concentrated on engineering design frequently revealed the success of engineering design-based learning is not a given (e.g., Dankenbring & Capobianco, 2015). To explore practical paths of STEM education, developing engineering design-based STEM modules in China primary science curriculum deserves more prominence (Margot & Kettler, 2019).

Therefore, to provide primary students with engaging and integrated STEM education experiences, this study targeted to develop an engineering design-based STEM (EDB-STEM) module with primary school science content, *force and motion*, for grade three students, and examined its effects on students' learning performance — specifically conceptual understanding of force and motion (CUFM) and motivation of STEM learning (MoL)—compared to a control group taught using the existing scientific inquiry-based modules from *Primary Science Teaching Design and Reflection* (PSTDR) instructional design series.

1.2 Background of the Study

This section begins with a brief overview of STEM education in the context of Chinese primary education, followed by an introduction to the study's central pedagogical framework: engineering design-based STEM (EDB-STEM) module. Then, the China's national primary science curriculum standards for force and motion was discussed, emphasizing their significance for Grade 3 students. Additionally, the section addresses the role of student motivation of STEM learning. Finally, it examines the current status of scientific inquiry within China's primary science education system, providing a foundation for contrasting it with the proposed EDB-STEM approach.

1.2.1 STEM Education in Chinese Primary Education

With increasing calls to improve students' engagement and increase graduates' numbers in science, technology, engineering and mathematics areas (NAE &NRC, 2011), STEM education has become a priority of international educational reform in the 21st century. Undoubtedly, it also closely relates to China' international competitiveness (Zhong et al., 2022). Since its first appear in China in 2001, many efforts, like curriculum standards or funding, have been put into practices to promote STEM in primary education. For example, the *Curricular Standards of Science in Elementary Schools*, issued by the Ministry of Education in 2017, set *technology and engineering* as one of the important areas of the primary science curriculum standards (MOE (China), 2017). Likewise, *13th Five-Year Plan for Educational Informatization*, released by Ministry of Education in 2016 (MOE (China), 2016), proposed that:

Good-condition regions should actively explore the application of information technology in new educational models such as 'crowd creation space', interdisciplinary learning (STEAM education), maker education, etc.

What makes STEM education popular is its features in the integrated authentic learning context which helps students to grasp connections between disciplines and address complex problems (NAE &NRC, 2011). In China, STEM education refers to a coherent cross-disciplinary and cross-stage curriculum series which includes discipline courses, like science courses, and integrated courses, aiming to develop 21st century skills and STEM literacy for all students (National Institute of Education Sciences [NIES](China), 2017). In other word, STEM education in China is not only about teaching subjects separately, for example, science or mathematics, but also emphasizes the integration of multiple STEM disciplines, such as teaching science concepts through the engineering design process. Learning separate STEM subjects from young age builds students systematically knowledge structure, while learning integrated STEM course cultivates students to apply knowledge synthetically and creatively (NIES (China), 2017). To meet the urgent demand of technology and engineering courses in the compulsory education, STEM education in China emphasized in integrating technology and engineering (NIES(China), 2017).

The integration of STEM into primary science education has created opportunities to address abstract scientific concepts, such as force and motion, through hands-on, engineering-based approaches. As previous studies recommended, science could incorporate habits of mind and practices with content knowledge learned from other disciplines (NRC, 2014). Science education thus provided a suitable platform to promote integrated education (MOE (China), 2017; Teng et al., 2019; Bybee, 2010; NRC, 2014). In primary schools, science has become a key subject through which STEM education is promoted, especially because of its emphasis on student development over academic performance (NIES (China), 2017). Since the release of the *Curricular Standards of Science in Elementary Schools* (MOE (China), 2017), which advocates for the integration of engineering principles into primary science education through interdisciplinary STEM learning approaches, primary science has served as the main avenue for delivering integrated STEM learning experiences, including those focused on physical science topics such as force and motion (Zhang et al., 2020; Daugherty et al., 2014; Xiao et al., 2019). For example, Li developed a series of STEM curriculum units that explicitly target students' conceptual understanding of force and motion. One such unit, *Sailing at Sea: Decomposition and Application of Force in STEM Curriculum* (Li, 2018), guided primary students to explore the concept of force decomposition and apply it to sailboat design. Through hands-on activities and iterative engineering design tasks, students were encouraged to synthesize scientific principles with practical problem-solving. Such examples reflect how primary STEM education in China has begun to integrate core physical science concepts with authentic engineering contexts to deepen conceptual understanding.

In 2022, 'Hundred Project-Based Learning Schools' Project was lunched in Zhejiang and selected 101 schools as the *Zhejiang STEM Education and Project-Based Learning Base School*. More than half of these schools are primary schools in eleven cities in Zhejiang. Meanwhile, international cooperation projects, like Zhejiang-Indiana Parallel Classroom Project (ZIPCP), are also on the way to boost the development of STEM education in primary education (Huang et al., 2022). It also has drawn researchers' attention to the potential of integrating fundamental science concepts with engineering practices in primary STEM education. For example, Lin (2016) chose Grade 3 science contents about plants to develop a STEM course--- *DIY plant wall*.

In light of the view that STEM could pave a path for young students toward future competitiveness, China has paid more attention to implement STEM education in primary science education (Wan et al., 2020) This emphasis aligns with national initiatives promoting applied learning approaches to enhance student engagement in STEM fields (NIES[China], 2017). Within this context, the concepts of force and motion have gained particular prominence due to their fundamental role in explaining everyday physical phenomena and their natural connections to engineering applications.

To maximize STEM education's potential in cultivating students' STEM literacy, effective STEM implementation requires pedagogical strategies that bridge abstract concepts (e.g., force and motion) with tangible applications. Engineering design, as a pedagogical strategy, serves as an ideal framework by engaging students in problem-solving while grounding their learning in meaningful science content. Therefore, in the context of Chinese primary education, implementing engineering-integrated STEM modules in science lessons is viewed as a practical and promising approach to improve students' understanding of force and motion as well as their STEM motivation. The following sections thus delve into engineering design and its operationalization in the proposed EDB-STEM module.

1.2.2 Engineering Design as A New Approach to STEM Education

Given its direct connection to problem-solving and innovation, it is crucial for the STEM education community to recognize the role of engineering design within compulsory education. Engineering design, which reflects the essence of engineering and is applied in real-world contexts (Kelley & Knowles, 2016), offers a hands-on, problem-solving learning model that emphasizes iterative thinking, creativity, and practical application—characteristics that make it especially suitable to achieve the integration of STEM learning.

Unlike passive absorption of knowledge, engineering design engages students in active reasoning processes, where they act as engineers to explore scientific concepts and interdisciplinary connections. The structured steps—*problem scoping,* *information collection, planning, design and create, test and redesign,* and *discuss*—mirror real-world engineering practices and foster skills like systems thinking and resilience (NRC, 2014). Critically, engineering design is not only intimately related to science and mathematics, it holds several important concepts. Firstly, engineering design targets problems from society with consideration of constraints. Design activities are initiated by explicit goals and shaped by a series of constraints. Secondly, as found by many researchers, engineering design could play as the catalyst for developing scientific and mathematical concepts while using technology (Moore et al., 2015; National Academies of Sciences, Engineering, and Medicine [NASEM], 2020). As noted by Guzey et al. (2014),

> *…to have students participate in engineering design as a mean to develop technologies that require meaningful learning and an application of mathematics and/or science (p.5).*

Following the introduction of the Next Generation Science Standards (NGSS) in 2013, which highlighted science and engineering practices as one of the three key dimensions of high-quality science education, educators and researchers in China started to take care necessities and value of engineering education in compulsory education. The *Curricular Standards of Science in Elementary Schools* (MOE (China), 2017) firstly mentioned the role of *technology and engineering* in primary science education, which enabled students enjoy the success and joy of doing and develop the habit of solving problems through personal hands-on work.

In recent years, several Chinese researchers have explored the nature and implementation of engineering education within primary and secondary settings. For example, by comparing scientific inquiry and engineering design, Shi and Li (2019) proposed that “S-E (science and engineering) integration” can be viewed as a great way for STEM curriculum model. Projects, lesson materials and plans towards STEM education were developed based on engineering design processes (Xu, 2019; Chen & Chen, 2019; Moore et al., 2015). For example, Zhou et al., (2020) took the *Spaceship Safety* by NASA as an example to explain how to develop STEM curriculum based on engineering design. To help students integrate science, technology, mathematic knowledge and improve their interests and motivation of STEM learning, Chen and Cheng (2019) developed one engineering design-based STEM lesson, *Building Structure Design*, for Chinese high school students. Moreover, some researchers further paid their attention to explore the effect of engineering design-based STEM activities on young students (Ayar, 2015; Shahali et al, 2017; English & King, 2015). For example, Xu (2019) found that students’ experiences on engineering design positively related to the change of students’ capabilities in handing complex task and their career interest in STEM.

These findings collectively highlight the pedagogical value of incorporating engineering design into science instruction—not only as a means to facilitate interdisciplinary integration, but also as a strategy to enhance students’ problem-solving abilities, engagement, and long-term motivation in STEM fields. By foregrounding engineering design as the approach to STEM education, educators could equip students with the mindset and tools to tackle tomorrow’s challenges—making it not just "present" in STEM, but purposeful and transformative.

1.2.3 Engineering Design-based STEM Module

Interweaving the content from science and mathematics curricula with engineering design, which provides the systematic problem-solving approach while creating authentic and engaging learning contexts, is a feasible and meaningful approach to achieve STEM. It represents a pedagogically viable and educationally meaningful strategy for achieving the integration of STEM learning. The Engineering Design-Based STEM (EDB-STEM) module is an instructional framework that unifies science, technology, engineering, and mathematics through an iterative engineering design process, fostering students' ability to construct meaningful interdisciplinary connections.

A typical EDB-STEM module comprises a series of thematically coherent lessons (e.g., centered on energy in primary science) where students progressively engage with each phase of the engineering design process. This culminates in the development of tangible artefacts, mirroring real-world engineering practices. By anchoring learning in societally relevant engineering challenges, these modules enable students to apply STEM knowledge within realistic contexts, learning from their failures (Guzey et al., 2016), thereby bridging theory and practice.

Under the wide attention to engineering design in policy documents, some research in China has dedicated to integrating engineering design with science concepts to develop engineering design-based STEM instructional materials. For example, Chen and Cheng (2019) adopted the 6E learning by doing model to develop an engineering design STEM module---building structure design, which focused on incorporate technical design, engineering design and the knowledge form science and mathematics to cultivate students' STEM literacy and learning interest.

In this study, students are administered to address one large engineering design challenge in the EDB-STEM module, namely designing and building an aerial delivery device that delivery necessaries for people in quarantine areas. The objectives of EDB-STEM module were to improve conceptual understanding among Grade 3 students about force and motion and increase students' motivation of STEM learning. To achieve that, it's also essential to know more about the primary science education and its basic learning approach in China.

1.2.4 Conceptual Understanding of Force and Motion in China

One critical way to help them understand things around them and take part in the science and technology-driven world is to teach students big ideas of science (Harlen, 2010, 2015). Force and motion, one big idea in science, has gotten much attention from China primary science education policy documents. Current policies and objectives about force and motion in Chinese primary science education can be traced back to the *Compulsory Education Science Curriculum Standards (Grade 3～Grade 6) (Trial Version)* (MOE (China), 2001), which highlighted "improve the scientific literacy of children" as the final purpose for primary science education. In that standard, learning *(i) motion and position, (ii) forces,* and *(iii) Newton's first law of motion* were identified as the main requirements of force and motion in primary science education.

With the advancement of research progression towards science concepts, children's early ideas about the world have started to reflect in the science curriculum standards in terms of progressive learning purpose. In *Curricular Standards of Science in Elementary Schools* (MOE (China), 2017), concepts of force and motion were taught to students from Grade 1. After preliminary learning directions and common forces like push and pull in Grade 1-Grade 2, the relationships between force and motion are being firstly taught in Grade 3 and has been integrated into the first chapter on the Grade 3 science textbook—*Objects' Motion* (Educational Science Publishing House, 2019). According to that standard, Grade 3 students were required to know (a) how to use objects' position to define others' position; (b)methods to measure distance and time; (c)speed; (d) characteristics of common motion; (e) common forces like friction, buoyancy, can affect objects directly; (f) the effects of force on objects' motion and shapes.

To further meet students' physical and mental development, the latest science curriculum standards, *Compulsory Education Science Curriculum Standards (2022 Edition)*, released in 2022 (MOE[China], 2022), put a high value on the connection of learning stages to make science curriculum more systematical and scientifically. According to the new standard, Newton's first law of motion was still the governing idea of force and motion for Grade 3 students. The fundamental ideas of speed, position, motion mentioned in the last standard were also emphasized. Therefore, the requirement for concepts of force and motion in China primary education consist of three parts (a) common forces, like gravity; (b) motion, (c) and the effects of forces, like Newton's first law of motion.

Learning science concepts is one primary purpose of science education. When students can think with, use, state and find an analogy for concepts, like energy, force in science, they have an understanding of concepts, namely *conceptual understanding*. *Force and motion* are fundamental concepts of science. Based on curriculum standards, understanding the force and motion, namely *conceptual understanding of force and motion* (CUFM), mainly talking about 'To change the motion of an object, a net force must act on it', consists of three constructs: conceptual understanding of force (CUF), conceptual understanding of motion (CUM), and conceptual understanding of Newton's first law of motion (CUNFLM).

Conceptual Understanding of Force and Motion (CUFM) has two key characteristics: connection and contextualization. First, one of the primary differences between experts and novices lies in how knowledge is organized. Young learners typically lack a well-structured knowledge framework (Hardiman, Dufresne, & Mestre, 1989). CUFM, being a central objective in science education, serves as an anchor that connects various ideas and helps establish comprehensive knowledge networks. This aligns with the STEM education goal of fostering a deep understanding of scientific concepts (NRC, 2011). Additionally, context dependence is another critical feature of students' CUFM. Contextual factors can activate and influence students' understanding of force and motion (Nie et al., 2019). Through science learning, students' pre-existing cognitive structures, which are often context-dependent, can be restructured and transformed into scientifically accurate perspectives.

The conceptual understanding of force and motion is not only important for students to aware links between human activities and the world (Harlen, 2010; NGSS, 2013; MOE (China), 2022), but also has a strong connection with students' STEM literacy (Bybee, 2010, 2013). For example, students' conceptual understanding of force is also essential to judge how interactions between objects change their motion (Aksit & Wiebe, 2020). Speed is one common concept in big idea of force and motion. Understanding the quantitative relationship between speed, time and distance is critical to grasp the mathematical model which cannot be obtained directly (Jin, 2019). To date, some studies have investigated students' conceptual understanding of force and motion in China, revealing that primary students in China have difficulties in conceptualizing force and motion (Chen, T, 2020; Yang, 2020; Jin, 2019). Wu (2018) investigated 82 Grade 3 to Grade 6 Chinese students' conceptual understanding of gravity and revealed that many students misunderstood the concept of gravity.

Given that foundational concepts of force and motion are formally introduced in Grade 3, the implementation of STEM education must prioritize its impact on conceptual understanding at this pivotal stage. Research underscores that early exposure to STEM experiences not only deepens conceptual mastery (e.g., discerning how forces alter motion), but also fosters motivation of STEM learning, a key affective mediator of long-term engagement and achievement (Ho & Liang, 2015).

1.2.5 Motivation of STEM Learning in China

Motivation, laying behind someone's acts or behaves, is the process of internalization which can divided into controlled and autonomous motivation based on the stage of internalization (Deci & Ryan, 2000). Deci and Ryan (2000) also mentioned that motivation can be viewed as the driving force to push students' learning and greatly impacts students' learning outcome. By analogy, motivation of STEM learning refers to the process to initiate, guide, promote and maintain behaviors to learn STEM, which has been treated as another important goal in STEM education. Motivated STEM learners are characterized by persistent and self-regulated, and more willing to participant in tasks related to STEM in various contexts (Luo et al., 2019).

Motivation is domain-specific (Tuan, 2005), with several key factors playing a crucial role in shaping students' engagement and success in STEM learning. These factors include self-efficacy, learning interest values (intrinsic motivation or task value), individual learning goals (comprising both performance and achievement goals), the perception of the learning environment, and learning strategies (self-determination or sense of autonomy). *Self-efficacy in STEM learning* refers to a student’s confidence in their ability to solve problems within the STEM disciplines. This confidence is a critical determinant of how students approach challenges and persist in their learning. *STEM learning interest values* involve the degree to which students are intrinsically motivated to understand and apply STEM concepts. This includes recognizing the relevance of STEM disciplines in everyday life, which can drive a deeper engagement with the subject matter. *STEM learning goals* are typically divided into performance goals, which focus on demonstrating competence in comparison to others, and achievement goals, which emphasize mastering content and improving personal skills. *Perception of STEM learning environment* encompasses the various elements of the learning context, including the outcomes of participating in a task, the influence of teaching strategies, and the interactions between students and teachers, as well as among peers. It also involves the broader cultural environment within the school and classroom. *STEM learning strategies* reflect students’ ability to choose and regulate their learning approaches, closely tied to their sense of autonomy and the personal importance they place on success in a task (Murphy et al., 2019). These strategies are essential for students to effectively manage and engage in their STEM education.

Increasing students’ motivation to learn STEM is a vital goal presented in the policy documents (NIES(China), 2017; MOE(China), 2022). As stated in *China STEM Education White Paper* (NIES (China), 2017), it’s necessary to pay attention to improve students’ STEM interests and motivation which would lay the foundation for their learning of STEM skills. A great deal of previous research into motivation has indicated that China primary students’ motivation has a positive relation with their learning outcomes (Wei, 2017; Li, 2019). Due to the relatively short history of STEM education in China, students' motivation of STEM learning receives little attention and stays at low level. For example, Jia et al. (2021) used descriptive statistical methods to analyze 164 Grade 3 students' learning motivation in a STEAM course in Beijing. As indicated in their findings, third-grade students lacked confidence in STEM learning due to the uncertainty they encountered in STEM learning. To improve students' performance in STEM learning, some researchers have dedicated to increase students' STEM motivation. For example, STEM lessons developed by Liang (2022) based on the influencing factors of students' motivation of STEM learning significantly increased students' motivation.

In all, enhancing students' conceptual understanding of core ideas, like force and motion, and motivation of STEM learning while solving real-world problems play a critical role to literate students and thereby deserve more attention.

1.2.6 Scientific Inquiry in the Primary Science Education in China

Scientific inquiry refers to the process by which students actively construct knowledge and understanding through asking questions, conducting investigations, collecting and interpreting evidence, and drawing conclusions. Rather than receiving facts passively, students are encouraged to think and act like scientists—raising testable questions, making predictions, experimenting, and explaining phenomena based on evidence (NRC, 2012). In 2017, Ministry of Education (MOE (China), 2017) released the *Curricular Standards of Science in Elementary Schools* which extended the learning time of science education (Hu & Shou, 2018), greatly promoting the development of primary science education in China. Scientific inquiry, the core problem-solving approach in science (NAE & NRC, 2009), has become the basic teaching and learning approach in primary science curriculum in China (Pei, 2019). According to the latest version of science education curriculum standards (MOE (China), 2022), the general processes of scientific inquiry in China science education include: (a) propose scientific questions and make reasonable hypotheses; (b)develop plans and collect evidence; (c)analyze evidence and draw conclusions; (d) interpret and evaluate results; finally (d) accurately express opinions, process and results of exploration.

This structured model of inquiry-based learning reflects a growing national emphasis on cultivating students' ability to explore the natural world using evidence-based reasoning, which aligns closely with international best practices in science education. Science education in Zhejiang province presents as the typical practice case of science education in China, as it's the only one province in China which has conducted integrated science since 1988 (Huang et al., 2016). Educators and policymakers in Zhejiang have paid many of their efforts to learn how to implement science education effectively from international science education research community (Wang, 2018). As the *Implementation Suggestions on Strengthening Science Education in Primary and Secondary Schools in the New Era* mentioned (Department of Education of Zhejiang Province, 2023):

> *... implement inquiry-based teaching, strengthen interdisciplinary and project-based learning driven by real problems…*

In light of the view that scientific inquiry stands for a critical principle for how science is conducted and supports the development of science (Bybee, 2006), the importance and value of scientific inquiry, one essential working approach of scientists to explore the natural world and propose explanations for natural phenomenon based on the evidence, were widely understood by science teachers in Zhejiang province through workshops and professional development (Wang, 2018). Scientific inquiry is not only the goal of primary science learning, but also the learning content in science

(Hu & Shou, 2018). Usually, teachers provide primary students a detail plan on how to set up experiments to investigate teacher-raised questions (Wu, 2020), which corresponds to structured-inquiry approach based on Buck et al. (2008) scheme of inquiry-based learning.

Scientific inquiry and engineering design share fundamental similarities as problem-solving approaches, yet they diverge in critical ways (NRC, 2009). Both are systematic reasoning processes used to navigate complex, uncertain challenges, employing cognitive strategies such as analogical reasoning, mental modeling, and iterative testing (Lewis, 2006). Scientists and engineers alike rely on creativity to develop hypotheses or design solutions, followed by rigorous evaluation—whether validating a scientific theory or refining a prototype. These parallels suggest potential synergies in integrating both approaches within educational curricula.

Key differences distinguish the two. Constraints, while present in both fields, are central to engineering design; budget limitations, for example, do not alter scientific truths but can render an engineering solution unfeasible. Similarly, trade-offs are intrinsic to design but largely irrelevant in scientific inquiry. Another divergence lies in their objectives: science seeks generalized principles from specific observations, whereas engineering applies universal principles to develop context-specific solutions. Values also play contrasting roles—design optimization is subjective and shaped by stakeholder preferences, whereas scientific conclusions ideally remain value-neutral. Methodologically, engineering embraces iteration and multiple viable solutions, while scientific inquiry typically progresses toward a single, evidence-based answer.

To advance scientific inquiry in science courses, researchers and educators have dedicated to developing science curriculum resources. For example, the *Primary*

Science Teaching Design and Reflection (PSTDR) instructional design series was conceptualized and developed by a team of primary science education experts from across the Zhejiang Province in response to a growing need to integrate scientific inquiry into science classrooms (Yu & Jiang, 2022). This instruction series is grounded in integrated science, which emphasized scientific inquiry as the major approach for students to learn science. In this study, a scientific inquiry-based instructional module from the PSTDR series was selected as the control group's instructional material, offering a representative model of inquiry-driven science education in China.

From the above study background, it can be seen that, improving students' conceptual understanding and their motivation of STEM learning are essential purpose of STEM education. In the context of the study, inquiry-based science instruction is the current standard practice in the participating school, whereas the EDB-STEM module represents an alternative, emerging instructional model that incorporates real-world problem solving through structured engineering design processes. While inquiry-based learning (IBL) and engineering design-based STEM (EDB-STEM) approaches differ in their specific aims and instructional processes, the comparison in this study is intentionally designed to explore how two pedagogical models commonly used in science education affect students' conceptual understanding and motivation for STEM learning.

1.3 Problem Statement

In the context of STEM education at the primary level in China, fostering students' conceptual understanding of science and enhancing their motivation for learning remain pressing challenges. In particular, fragmented understanding is common among students when learning about fundamental physical science topics such as force and motion. Furthermore, students' motivation of STEM learning tends to decline over time, affecting their engagement and interest in science. While scientific inquiry is a core instructional approach promoted in primary science education, its implementation in classroom practice is often hindered by issues such as teachers' limited pedagogical understanding, and lack of resources. In addition, although engineering design has been recognized internationally as a catalyst for meaningful STEM integration, its practical application in Chinese primary science classrooms remains limited. This highlights a need to explore how engineering design can be integrated effectively into science education to support students' understanding and motivation.

1.3.1 Challenges in Understanding Force and Motion Among Primary Students in China

Force and motion, as fundamental concepts in science education, are essential for explaining a wide range of natural phenomena (Harlen, 2010). However, previous studies have shown that many primary students in China struggle to achieve the level of conceptual understanding of force and motion required by the science curriculum standards. For instance, Li (2015) revealed that more than 50% students participating the study didn't meet the required conceptual understanding of force and motion in science curriculum standards even after their primary education. Similarly, other studies have indicated that students often face persistent difficulties in grasping these core concepts (Neumann et al., 2013; Aksit & Wiebe, 2020). The same problem also arises in each construct of conceptual understanding of force and motion. In the study of Hao (2020), it's found that primary students' conceptual understanding of force was inconsistent with learning progressions in curriculum standards and disconnected with the contexts of these concepts. Take the gravity as example, Wu (2018) found that

Grade 3 students' conceptual understanding of gravity was inconsistent with its scientific meaning. In terms of motion, Zhang (2021) also revealed that primary students in China have difficult in calculating objects' speed by distance and time. Similar findings also occurred among senior students (Nie et al., 2019; Liu & Fang, 2016). Newton's first law of motion, as one of the key parts of understanding the concepts of force and motion, is also difficult for students. In the study of Chen (2020), less than 40% of primary students understood that force can change the motion of an object. How to support primary students' learning of disciplinary knowledge remains largely on empirical enterprise in which more detail information is needed.

1.3.2 Low Motivation of STEM learning in Primary education

Students' learning motivation has a positive effect in improving students' initiative and retention in STEM learning. However, in China, scholars paid much attention to investigate college students' motivation in foreign language learning rather than in primary STEM learning. Prior studies revealed that Chinese students' motivation of STEM learning stayed at low level and faded with grades ((Du, 2018; Fan, 2020; Zhang, 2017; Zhou & Zhang, 2023; Ding, 2012), meaning that students might be less inclined to engage in learning activities for success in STEM careers. Jia et al. (2021) used descriptive statistical methods to analyze 164 Grade 3 students' learning motivation of STEM. The findings indicate that third-grade students who relate STEM learning to their daily lives generally express satisfaction with their learning experiences. However, despite this positive attitude, they often lack confidence or self-efficacy in STEM subjects due to the uncertainties they encounter in these learning activities. In a five-year longitudinal study, Jia et al (2012) revealed that students' surface and achievement motivation showed a descending trend, indicating that, from Grade 1 to Grade 3, the higher the grade was, the lower students' motivation were. Primary school classrooms in China are often teacher-led in which students' need for autonomy has not been met, making it difficult for students to choose suitable learning strategies in STEM learning and maintain high achievement motivation (Xu, 2022), and leading to a negative perception of STEM learning environment (Tuan, 2005).

1.3.3 Limitations of Scientific Inquiry in Science Classrooms

As one of the elements of STEM education, science education plays as one essential role in implementing STEM education in schooling. And scientific inquiry is supposed to be the basic teaching method in China primary science courses (Hu & Shou, 2018). However, the scientific inquiry does not effective in improving students conceptual understanding of science concepts and motivation of science learning and cannot satisfy the requirements of STEM education (Mei, 2022; Tang & Ding, 2012; Lu & Bi, 2015). One of the main reasons is that many students' views about scientific inquiry didn't match the informed understanding of scientific inquiry (Zheng et al., 2022; Lederman et al., 2019). As it has been misinterpreted by many as a synonym for scientific method, scientific inquiry didn't meet expectation in practice (Emden, 2021; Lu & Bi, 2015; NSTA, 2018; Tang & Ding, 2012). A great deal of previous research into scientific inquiry has found that students were not able to understand connections between science concepts because the knowledge in science learning becomes desocialized from its generative contexts (Emden, 2021; Meng & Shi, 2015).

In addition, the study by Li et al. (2018) showed that inquiry activities in five science textbooks in China were not conducive to develop students' scientific inquiry skills. Wang et al. (2021) and Lee and Wan (2022) further revealed that although science textbooks covered STEM content, it put uneven emphasis on physical science. High-quality STEM curricula are crucial to improve STEM education (Margot &

Kettler, 2019; Asghar et al., 2012). Some studies revealed that students, even after receiving primary education, still have difficulties in understanding scientific inquiry (Lederman et al., 2019; Zheng et al., 2022). Therefore, more efforts are still needed to design high-quality integrated STEM curriculum and to explore the potential to deliver STEM curriculum in an interdisciplinary way (Thibaut et al, 2018).

1.3.4 Limited Application of Engineering Design in STEM

To promote STEM education, engineering has been emphasized and included in K-12 education standards (NGSS, 2013; MOE (China), 2017). Engineering design, highly associated with creation and improvement of the design artefact, provides authentic contexts for learning and enable students to apply the knowledge in problem-solving (Stammes et al., 2022; Marulcu, 2014; King & English, 2016; English et al., 2017; Delen & Yuksel, 2022; Ladachart et al., 2022). Although engineering is a core component of STEM, not all STEM implementations systematically adopt the structured engineering design process (EDP). In many STEM curricula, engineering aspects may remain implicit or be limited to hands-on activities without guiding students through the iterative processes of problem identification, idea generation, prototyping, testing, and redesign.

Moreover, studies focusing on engineering design have emphasized that the success of engineering design-based learning is not guaranteed (e.g., Dankenbring & Capobianco, 2015). In China, the use of the engineering design process in STEM education is still not widespread. Studies about engineering design mostly concentrated on how to design engineering design-based program, rather than on its impacts on students' understanding or motivation with the support of empirical evidence. For example, Zhou et al. (2020) analysed the engineering design-based STEM curriculum, *Spacecraft Safety*, developed by NASA and then provided suggestions to develop STEM curriculum. Some previous studies have provided suggestions to design engineering design-based STEM modules. However, most of them weren't designed (a) in line with the requirements of science curriculum; (b) based on uniform engineering design process; (c) for Chinese primary students (Liu et al., 2020; Zhou et al., 2020; NASEM, 2020).

By explicitly integrating the engineering design process into the intervention, the present study aims to provide students with authentic problem-solving experiences that reflect real-world engineering practices. This structured approach ensures that students engage meaningfully with each phase of the design cycle, thereby enhancing their conceptual understanding of scientific principles and increasing their motivation to learn STEM. This approach aligns with prior research, which suggests that teaching the engineering design process explicitly can lead to greater cognitive and motivational gains, especially in primary and middle school contexts where structured design thinking is often underutilized. Furthermore, comparing the effects of engineering design with those of currently used scientific inquiry approaches in science classrooms may offer insights into the relative advantages and limitations of engineering design as an instructional strategy.

1.4 Purpose of the Study

As mentioned above, there were little research that investigated the impacts of engineering design-based STEM education on primary students' learning performance in China. Given that the explicit integration of engineering design with science contents plays a crucial role in STEM education, it's worthy to pay attention to explore how engineering design can be effectively incorporated into school science curricula. Therefore, this study aims to (a) develop the engineering design-based STEM (EDB-