



## Interdisciplinary Integration Across Four Design Cases in Engineering Design-Based STEM: Implications for TPCK Development in Elementary Teacher Education

Chittamas Suksawang

Program of Curriculum and Instruction, Faculty of Education, Surindra Rajabhat University

Corresponding author, E-mail: chittamas.s@sru.ac.th

### ABSTRACT

This study investigates how Engineering Design-Based STEM activities foster interdisciplinary integration and support the development of Technological Pedagogical Content Knowledge (TPCK) among second-year elementary student teachers. The research was conducted with 30 second-year student teachers enrolled in a Learning Management in Science for Elementary School Teachers course at a regional university in northeastern Thailand during the second semester of the 2025 academic year. The instructional intervention consisted of four Engineering Design-Based STEM projects: Projectile Launcher, Wind Direction Indicator, Eco-Water Turbine, and Wind-Powered Car. Each activity followed six stages of the Engineering Design Process (EDP): problem identification, idea generation, solution design, implementation, testing and refinement, and presentation. This study employed an exploratory sequential mixed-methods design. Qualitative data were collected from STEM design documents, prototypes, classroom observations, reflective journals, and focus group interviews to examine patterns of interdisciplinary integration during the design process. Quantitative data were obtained using a TPCK self-assessment questionnaire measuring seven TPCK components (CK, PK, TK, PCK, TCK, TPK, and TPCK). The instrument demonstrated acceptable internal reliability (Cronbach's  $\alpha = .92$ ). Quantitative data were analyzed using mean and standard deviation. The findings reveal that interdisciplinary integration emerged through concept-driven engineering challenges that requiring coordinated scientific, mathematical, and technological reasoning. The Engineering Design Process functioned as an epistemic scaffold guiding iterative testing and refinement. Technology was primarily used as a tool for measurement, analysis, and prototype optimization rather than presentation. Descriptive statistics indicated that all TPCK components reached a high level ( $M = 4.29$ ,  $S.D. = 0.58$ ), with Pedagogical Content Knowledge showing the highest mean score. These findings suggest that Engineering Design-Based STEM activities provide meaningful opportunities for fostering integrative professional knowledge among elementary student teachers.

**Keywords:** STEM education, Engineering Design Process, Technological Pedagogical Content Knowledge, Elementary Teacher Education

## 1. Introduction

In the era of digital transformation, emerging technologies increasingly shape knowledge-based societies and redefine expectations for educational systems. Schools are no longer tasked solely with transmitting disciplinary knowledge but must cultivate learners' competencies in critical thinking, problem solving, collaboration, and adaptive application of knowledge in authentic contexts (OECD, 2018; Voogt et al., 2018). Consequently, teachers are expected to design learning experiences that effectively integrate subject matter, pedagogy, and technology in coherent and context-responsive ways. This integrative competence has been conceptualized through the framework of Technological Pedagogical Content Knowledge (TPCK), introduced by Mishra & Koehler (2006) as a critical professional knowledge base for teaching in the digital age. Building upon Shulman's (1987) concept of Pedagogical Content Knowledge (PCK), TPCK emphasizes that effective teaching emerges not from isolated knowledge domains but from the dynamic interaction among Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK), along with their intersecting domains (Koehler & Mishra, 2008). High-quality instruction, therefore, depends on teachers' ability to transform subject matter through pedagogically appropriate strategies while leveraging technological affordances aligned with learners' needs and contextual conditions (Chai et al., 2019; Tondeur et al., 2020). This paradigm shift reflects a broader movement away from transmission-based models of instruction toward competency-oriented and constructivist approaches (Darling-Hammond et al., 2017). Teachers are increasingly positioned not merely as knowledge transmitters but as designers of learning environments and facilitators of knowledge construction. Effective instruction requires the orchestration of meaningful learning experiences in which students actively engage with real-world problems and construct understanding through inquiry, reflection, and collaboration (Schmidt et al., 2021).

Despite the theoretical advancement of TPCK, persistent challenges remain in its systematic development within teacher education programs. In the Thai context, particularly within Rajabhat Universities, second-year elementary student teachers face unique hurdles in achieving interdisciplinary integration. Unlike secondary education specialists, elementary student teachers are prepared as generalists responsible for multiple subject areas. This broad scope often results in fragmented disciplinary knowledge, making it difficult for them to perceive deep conceptual connections between Science, Mathematics, and Engineering (Thibaut et al., 2018; Chai et al., 2021). Furthermore, while these student teachers are proficient in social media, they often struggle with the Technological Content Knowledge (TCK) required to use technology as an epistemic tool, such as using sensors for data collection or software for mathematical modeling. Research indicates that they often view technology merely as a presentation aid, failing to bridge the gap between digital literacy and integrative pedagogical reasoning (Howard et al., 2022). Consequently, there is a critical need to understand how teacher education can move beyond additive technology use toward a transformative Synthetic TPCK that is context-responsive to the primary classroom.

Empirical research consistently indicates that student teachers often demonstrate relatively strong Technological Knowledge (TK) but struggle to integrate technology meaningfully with disciplinary epistemology and pedagogical reasoning (Voogt et al., 2018; Chai et al., 2021; Schmid et al., 2021). In Thailand, particularly within Rajabhat



Universities—whose mission emphasizes producing teachers for local and community development—second-year elementary student teachers continue to experience difficulties in achieving coherent TPCK integration. Although contemporary student teachers are frequently described as digital natives, familiarity with everyday technology use does not automatically translate into pedagogically meaningful integration. Research has shown that student teachers often conceptualize technology primarily as a presentation tool rather than as an epistemic instrument that supports inquiry, conceptual modeling, and higher-order thinking (Howard et al., 2022; Koh et al., 2022). Moreover, teacher education programs in many higher education institutions remain dominated by lecture-based instruction and classroom-bound practicum experiences (Tondeur et al., 2017; Instefjord & Munthe, 2017). Such structures limit opportunities for student teachers to confront authentic, context-rich situations that demand integrative decision-making across content, pedagogy, and technology. As a result, technological integration may remain superficial and additive rather than transformative (Chai et al., 2019). Recent scholarship further indicates that while student teachers frequently report high TK, they encounter greater difficulty developing Technological Content Knowledge (TCK) and fully integrated TPCK, particularly when designing inquiry-oriented learning environments (Schmid et al., 2021; Voogt et al., 2023). This highlights a persistent gap between digital literacy and integrative pedagogical reasoning.

Addressing this gap requires learning environments that structurally compel coordination across knowledge domains. STEM education grounded in Engineering Design-Based STEM learning has emerged as a promising strategy (Kelley & Knowles, 2016; English, 2020). For elementary student teachers, the Engineering Design Process (EDP) functions as an epistemic scaffold, forcing them to coordinate Pedagogical Knowledge (PK)—such as classroom management during hands-on activities—with Technological Knowledge (TK) used in prototype optimization. Specifically, in primary education, TPCK development must emphasize the transformation of complex engineering concepts into age-appropriate, inquiry-based experiences. By situating TPCK within design-based challenges, student teachers must engage in iterative decision-making that aligns disciplinary content with pedagogical strategies and technological affordances (Radloff & Guzey, 2021). Integrated STEM emphasizes the coordination of science, technology, engineering, and mathematics to address complex problems reflective of real-world practice (Bybee, 2013; Thibaut et al., 2018). In particular, Engineering Design-Based STEM learning situates disciplinary concepts within ill-structured challenges that require iterative refinement and evidence-based reasoning (Moore et al., 2014; Hynes et al., 2020). Such environments move beyond isolated content delivery toward interdisciplinary problem-solving experiences. When student teachers engage in design-based STEM tasks, they must dynamically coordinate disciplinary understanding, pedagogical reasoning, and technological tools to respond to contextual constraints and emergent variables (Radloff & Guzey, 2021; Dare et al., 2021). This process aligns with experiential and situated learning theories (Kolb, 1984; Lave & Wenger, 1991), which conceptualize knowledge as constructed through participation in authentic practice. Engineering Design Process (EDP) cycles—identifying problems, generating solutions, testing prototypes, and refining designs—embed disciplinary reasoning within iterative material engagement (Pleasant & Olson, 2021). Within such contexts, technology functions not merely as a delivery mechanism but as an epistemic tool that supports data collection, analysis, modeling, and

optimization (Howard et al., 2022). By requiring participants to test and revise solutions, design-based STEM environments create conditions under which disciplinary knowledge, pedagogy, and technology must be coordinated in practice. Consequently, structured Engineering Design-Based STEM activities may provide fertile conditions for the enactment and development of TPCK.

The present study, conducted at a Rajabhat University in northeastern Thailand, seeks to fill these gaps by leveraging authentic local contexts as design laboratories. While general TPCK research is abundant, there is a lack of empirical evidence specifically examining how the iterative nature of EDP—from problem identification to refinement—targets the development of TPCK components in pre-service elementary teachers who lack specialized disciplinary backgrounds. This research addresses this practice-to-theory gap by identifying which elements of TPCK are most effectively fostered when generalist student teachers are challenged to design interdisciplinary solutions for real-world local problems. These contextual assets align with the university's mission of producing innovative teachers for sustainable local development. By leveraging authentic local environments as learning laboratories, second-year elementary student teachers are encouraged to design interdisciplinary STEM experiences grounded in community realities. Embedding design-based STEM activities within place-responsive contexts potentially strengthens TPCK development by situating integrative reasoning within real-world constraints. Although substantial literature exists on TPCK development and STEM education, relatively few empirical studies have examined the development of TPCK through structured Engineering Design-Based STEM learning within teacher preparation programs (Chai et al., 2021; Radloff & Guzey, 2021). Most prior research has focused on classroom-based technology integration or online learning environments rather than design-driven, performance-based contexts. Furthermore, within the Rajabhat University system—where place-based identity and local development missions are central—there remains limited empirical evidence explaining how Engineering Design-Based STEM instructional design supports TPCK development among second-year elementary student teachers. Additionally, insufficient research has identified which TPCK components are most strongly enhanced through structured EDP implementation in authentic settings. Addressing this gap is critical for understanding how interdisciplinary STEM experiences can move student teachers beyond technological familiarity toward integrated professional competence.

### **Research Objectives**

1. To examine how Engineering Design-Based STEM activities foster interdisciplinary integration across science, technology, engineering, and mathematics; and
2. To evaluate the development of TPCK components following the implementation of Engineering Design-Based STEM activities.



## 2. Conceptual Framework

### 2.1 STEM Education in Elementary Education

Interdisciplinary integration has become a central principle of contemporary STEM education, particularly in elementary contexts where foundational conceptual development is critical. Rather than positioning science, technology, engineering, and mathematics as discrete and compartmentalized subjects, integrated STEM education emphasizes the purposeful coordination of disciplinary knowledge to address authentic and complex problems (Kelley & Knowles, 2016). This integrative orientation reflects the epistemic practices of scientific and engineering communities, in which knowledge is applied across disciplinary boundaries to design, test, evaluate, and refine solutions. In elementary education, STEM integration serves not only to deepen conceptual understanding but also to cultivate problem-solving skills, collaborative reasoning, and adaptive thinking. When young learners engage in interdisciplinary challenges, they are required to connect scientific principles, mathematical reasoning, technological tools, and engineering processes in meaningful ways. Such experiences foster a more coherent understanding of how knowledge functions in real-world contexts rather than as isolated academic content. Despite its theoretical promise, interdisciplinary STEM integration remains pedagogically demanding. Empirical research indicates that teachers frequently implement STEM in parallel or thematic formats, where disciplinary elements are presented side by side without substantive conceptual coordination (Bybee, 2013). In these approaches, science, mathematics, and technology may coexist within a single lesson, yet remain structurally disconnected. As a result, opportunities for integrative reasoning are limited, and disciplinary knowledge remains compartmentalized rather than functionally interconnected.

Effective interdisciplinary STEM instruction, therefore, requires explicit structural mechanisms that intentionally scaffold integration. Integration does not emerge automatically from the inclusion of multiple disciplines; it must be guided through carefully designed instructional frameworks that require coordinated reasoning across domains. Among the proposed models, the Engineering Design Process (EDP) has gained prominence as a structural organizer for interdisciplinary STEM learning. The EDP typically includes stages such as identifying a problem, researching relevant information and constraints, generating and selecting possible solutions, constructing prototypes, testing performance, evaluating results, and refining designs through iterative improvement. Because each stage necessitates scientific explanation, technological decision-making, mathematical evaluation, and engineering judgment, the EDP functions as a coherent framework for interdisciplinary coordination. In elementary education, the EDP provides a developmentally appropriate mechanism for integrating abstract disciplinary concepts within tangible design tasks. By embedding scientific inquiry and mathematical reasoning within purposeful construction activities, the EDP transforms interdisciplinary STEM from a thematic alignment into a structured epistemic process. Consequently, the Engineering Design Process serves not merely as an instructional strategy but as a mediating structure that enables functional integration across STEM domains.

## 2.2 Engineering Design Process (EDP) as a Mediating Structure for STEM Integration

Engineering design-based learning situates disciplinary knowledge within purposeful and authentic construction tasks. Unlike conventional problem-solving activities characterized by predetermined procedures and single correct answers, engineering design challenges are typically ill-structured and context-dependent. Such challenges require iterative refinement, evidence-based reasoning, and adaptive decision-making. In this way, engineering design aligns with inquiry-based science education while extending it through material construction, optimization, and performance evaluation.

Research has demonstrated that engineering design promotes deeper conceptual understanding by embedding abstract scientific principles within tangible and functional applications (Moore et al., 2014). For instance, the concept of energy transformation becomes more meaningful when learners must optimize mechanical efficiency within a working prototype. Similarly, understanding force and motion is strengthened when structural instability reveals the consequences of misaligned design decisions. Through such embodied experiences, disciplinary concepts move beyond theoretical abstraction and become operationalized within real design constraints. Moreover, engineering design distributes cognitive demand across collaborative teams, fostering explanation, negotiation, and shared reasoning. Iterative testing and revision encourage learners to engage in metacognitive reflection, analyzing why a prototype succeeded or failed and how modifications influence performance outcomes. This reflective cycle supports not only conceptual development but also epistemic awareness of how knowledge is constructed, tested, and refined.

In teacher education contexts, engineering design-based learning may be particularly powerful. The student teachers are required not only to understand disciplinary content but also to consider how such knowledge can be pedagogically transformed for learners. Engaging in design cycles compels them to integrate content understanding, instructional strategy, and technological decision-making within authentic problem-solving environments. The Engineering Design Process (EDP) provides the structural foundation for such integrative learning. The EDP commonly comprises six interconnected stages: Identifying the problem, Gathering information and generating ideas related to the problem, Designing possible solutions, Planning and implementing the solution, Testing, evaluating, and improving the solution or revising the prototype, and Presenting the solution, problem-solving process, or final product.

Rather than functioning as a linear checklist, these stages form an iterative cycle in which evidence gathered during testing informs subsequent redesign. As a mediating structure, the EDP compels learners to coordinate scientific reasoning, mathematical evaluation, technological tool use, and engineering optimization within a unified problem-solving framework. Consequently, the Engineering Design Process serves not merely as an instructional strategy but as an epistemic scaffold that supports interdisciplinary integration across STEM domains.

## 2.3 Technological Pedagogical Content Knowledge in Teacher Education

Technological Pedagogical Content Knowledge (TPCK), introduced by Mishra & Koehler (2006), extends Shulman's (1987) concept of Pedagogical Content Knowledge (PCK) by incorporating technological knowledge as an



essential dimension of teacher expertise in contemporary educational contexts. The TPCK framework conceptualizes effective teaching with technology as the dynamic and context-sensitive interaction among three core knowledge domains: Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK). Importantly, the framework emphasizes not the isolated possession of these domains, but their intersections—Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and the fully integrated Technological Pedagogical Content Knowledge (TPCK) (Koehler & Mishra, 2008). Within this model, technology is not positioned as an additive instructional tool layered onto existing teaching practices. Rather, it is conceptualized as a transformative element that reshapes how subject matter is represented, explored, and understood. Effective integration requires teachers to recognize how specific technological affordances can support conceptual visualization, address learner misconceptions, facilitate inquiry, and scaffold higher-order thinking.

Despite the theoretical robustness of the TPCK framework, empirical studies consistently indicate that student teachers encounter challenges in achieving meaningful integration. Research suggests that while student teachers often demonstrate relatively strong Technological Knowledge (TK)—particularly in everyday digital applications—they frequently struggle to align technological tools with disciplinary epistemology and pedagogical purpose (Voogt et al., 2013). Technological Content Knowledge (TCK) and fully integrated TPCK commonly emerge as developmental areas of difficulty, reflecting the cognitive complexity of coordinating content transformation, instructional strategy, and technological affordance simultaneously. These findings suggest that integrative TPCK competence does not develop through exposure to technology alone, nor through isolated coursework in educational technology. Rather, it requires structured, practice-based experiences that compel student teachers to engage in coordinated reasoning across domains. Design-based STEM instruction offers one such structured context. Engineering challenges require decisions about which technological tools are appropriate, how disciplinary concepts should be represented, and how learning experiences should be structured to support conceptual understanding. In such environments, technology functions as an epistemic instrument—supporting data collection, modeling, simulation, measurement, and optimization—rather than merely serving as a medium for content presentation. Consequently, Engineering Design-Based STEM activities may provide authentic conditions for TPCK enactment, as they embed technological decision-making within iterative cycles of disciplinary reasoning and pedagogical transformation.

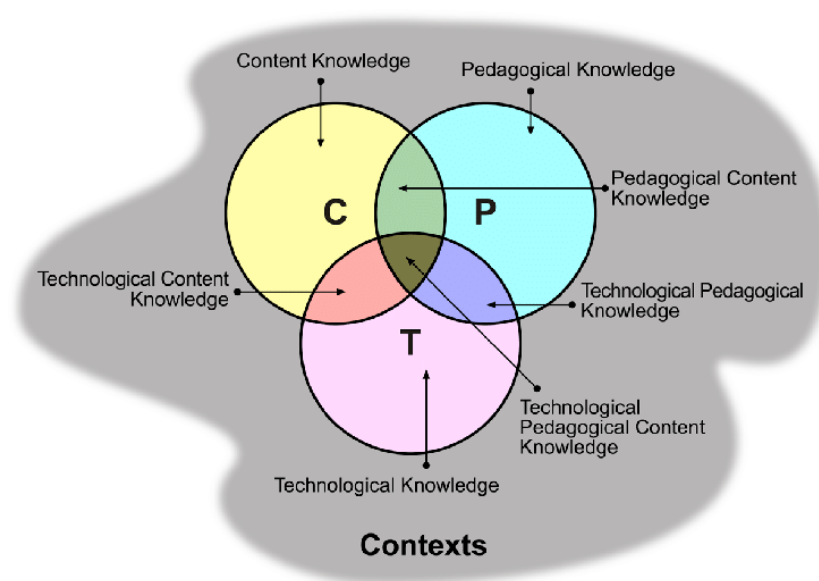


**Figure 1.** Technological Pedagogical Content Knowledge (TPCK) framework and its knowledge components (Koehler & Mishra, 2008)

Figure 1 illustrates the TPCK framework as a model of intersecting knowledge domains. The three primary circles—Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK)—intersect to form four additional integrative domains: PCK, TCK, TPK, and the central TPCK. The model visually represents the idea that effective technology integration in teaching emerges from the dynamic interplay among these domains rather than from isolated expertise in any single area.

## 2.4 STEM Design Activities and TPCK Development

Emerging scholarship suggests that experiential and design-oriented learning environments play a critical role in fostering integrative professional knowledge among student teachers. In contrast to lecture-based instruction or isolated technology training, design-based STEM activities require participants to construct artifacts, test prototypes, analyze performance data, and iteratively refine solutions. Such processes compel student teachers to engage simultaneously with disciplinary concepts, pedagogical structuring, and technological affordances. Integration, therefore, becomes enacted rather than merely conceptualized. Within Engineering Design-Based STEM contexts, content knowledge informs design decisions; pedagogical reasoning shapes collaborative inquiry and task sequencing; and technology functions as a tool for measurement, modeling, simulation, or optimization. These environments demand coordinated decision-making across domains, thereby creating authentic conditions for TPCK development. Kolb's (1984) experiential learning theory provides a useful theoretical lens for understanding how such integration unfolds. According to Kolb, learning progresses through iterative cycles of concrete experience, reflective observation, abstract conceptualization, and active experimentation.



Engineering Design-Based STEM learning closely parallels this experiential cycle. Each design iteration requires participants to test ideas in material form, reflect on outcomes, revise conceptual understanding, and implement improved solutions. Through repeated cycles of experimentation and refinement, disciplinary knowledge becomes situated, technologized, and pedagogically transformed. Importantly, this iterative design process may be particularly valuable in teacher education contexts. Student teachers are not only required to understand STEM concepts but must also consider how those concepts can be transformed into meaningful learning experiences for elementary students. Design-based activities make these transformation decisions explicit: participants must determine which tools support conceptual clarity, how tasks should be scaffolded, and how evidence should be interpreted. In doing so, they move beyond isolated technological familiarity toward integrative professional reasoning.

Despite increasing attention to STEM integration and TPCK development, empirical research remains limited in several respects. First, relatively few studies have examined how structured Engineering Design-Based STEM activities specifically support the development of individual TPCK components—such as TCK, TPK, and fully integrated TPCK—among second-year elementary student teachers. Second, existing research often focuses on single design interventions or isolated projects, leaving unexplored how interdisciplinary integration unfolds across multiple design cases within a single teacher education course. Consequently, there is limited understanding of how different design contexts—varying in scientific focus, technological demands, and engineering constraints—collectively contribute to the development of integrative professional competence. Addressing these gaps requires systematic examination of interdisciplinary integration across multiple structured design cases, with attention to how such experiences mediate the development of TPCK components in early-stage teacher preparation.

### 3. Methodology

#### 3.1 Research Design

This study employed a mixed-methods research design to examine how Engineering Design-Based STEM activities supported interdisciplinary integration and the development of Technological Pedagogical Content Knowledge (TPCK) among student teachers. The research followed a two-phase sequential design, in which qualitative data were first used to explore the processes of interdisciplinary integration during STEM design activities, followed by quantitative analysis to evaluate the level of TPCK development after the instructional intervention.

##### **Phase 1: Qualitative exploration of interdisciplinary integration.**

The first phase focused on examining how interdisciplinary reasoning across science, technology, engineering, and mathematics emerged during the implementation of Engineering Design-Based STEM activities. Qualitative data were collected from multiple sources, including STEM design documents, engineering prototypes, classroom observations, reflective journals, focus group interviews, and the researcher's field notes. These data were analyzed using thematic analysis to identify patterns of interdisciplinary coordination, technological decision-making, and pedagogical reasoning within the Engineering Design Process (EDP).

**Phase 2: Quantitative evaluation of TPCK development.**

Following the completion of all STEM design activities, quantitative data were collected using a TPCK self-assessment questionnaire measuring seven knowledge domains: Content Knowledge (CK), Pedagogical Knowledge (PK), Technological Knowledge (TK), Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and integrated Technological Pedagogical Content Knowledge (TPCK). The questionnaire responses were analyzed using descriptive statistics, including mean scores and standard deviations, to determine the level of TPCK development among participants.

**Integration of qualitative and quantitative findings.**

The integration of the two data strands occurred during the interpretation stage. Qualitative findings describing interdisciplinary design practices and engineering design cycles were used to explain the patterns observed in the quantitative TPCK results. This integration enabled a comprehensive understanding of how Engineering Design-Based STEM experiences contributed to the development of integrative professional knowledge among student teachers.

**3.2 Participants and Context**

The participants in this study consisted of 30 second-year elementary student teachers enrolled in a Learning Management in Science for Elementary School Teachers course during the second semester of the 2025 academic year at a regional university in northeastern Thailand. The participants were selected using purposive sampling, as they were members of the intact class in which the Engineering Design-Based STEM instructional intervention was implemented. This group was considered appropriate for the study because the course focused specifically on science learning management and STEM instructional design for elementary education.

At the time of the study, the participants had completed foundational coursework in education and basic educational technology, but had limited prior experience with interdisciplinary STEM integration or engineering design-based instruction. The course, therefore, provided an appropriate context for examining the development of Technological Pedagogical Content Knowledge (TPCK) through structured STEM learning experiences. The instructional intervention was implemented throughout one academic semester and involved four Engineering Design-Based STEM projects: Projectile Launcher, Wind Direction Indicator, Eco-Water Turbine, and Wind-Powered Car. Each project required participants to apply scientific principles, mathematical reasoning, technological tools, and engineering design strategies in order to design, construct, test, and refine functional prototypes. All STEM learning activities were organized according to the Engineering Design Process (EDP), which consisted of six stages: identifying the problem, gathering information and generating ideas, designing possible solutions, planning and implementing the solution, testing, evaluating, and improving the prototype, and presenting the final solution and design rationale.

The research was conducted in accordance with established ethical principles for educational research. All participants were informed about the purpose of the study and provided voluntary informed consent prior to participation. Participants were assured that their participation was voluntary and that they could withdraw from the study at any



time without any consequences. All collected data were used solely for research purposes, and participants' identities were anonymized to ensure confidentiality during data analysis and reporting.

### **3.3 Data Collection**

Data were collected throughout the implementation of Engineering Design-Based STEM activities conducted in the Learning Management in Science for Elementary School Teachers course during the second semester of the 2025 academic year. The instructional intervention consisted of four Engineering Design-Based STEM projects: Projectile Launcher, Wind Direction Indicator, Eco-Water Turbine, and Wind-Powered Car. Each project was organized according to the six stages of the Engineering Design Process (EDP): identifying the problem, gathering information and generating ideas, designing possible solutions, planning and implementing the solution, testing and improving the prototype, and presenting the final solution and design rationale.

#### **Qualitative Data Collection**

Qualitative data were collected during the STEM design activities to examine how interdisciplinary integration and TPCK-related reasoning emerged during the design process. Multiple sources of qualitative data were used to ensure data triangulation, including:

1. STEM design documentation and presentations, which described participants' design rationale and interdisciplinary problem-solving strategies;
2. Engineering prototypes and testing records, documenting the iterative refinement of designs throughout the Engineering Design Process;
3. Classroom observations, focusing on collaborative inquiry, technological decision-making, and interdisciplinary reasoning during STEM activities;
4. Reflective journals, in which participants documented their learning experiences, conceptual understanding, and challenges encountered during the design process;
5. Focus group interviews, conducted after the completion of the STEM activities to explore participants' perceptions of interdisciplinary STEM integration and instructional decision-making;
6. Field notes of Observation, which recorded key observations and emerging patterns of integration during the intervention.

#### **Quantitative Data Collection**

Quantitative data were collected after the completion of all four STEM design projects using a Technological Pedagogical Content Knowledge (TPCK) self-assessment questionnaire. The questionnaire was designed to measure seven TPCK components: Content Knowledge (CK), Pedagogical Knowledge (PK), Technological Knowledge (TK), Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and Technological Pedagogical Content Knowledge (TPCK).

### **Instruments**

The quantitative data were collected using a Technological Pedagogical Content Knowledge (TPCK) self-assessment questionnaire designed to measure preservice teachers' perceived competence in integrating content knowledge, pedagogy, and technology in STEM learning contexts. The questionnaire was developed based on the TPCK framework proposed by Koehler & Mishra (2008) and adapted from previously validated TPCK instruments used in teacher education research. The instrument consisted of 30 items measured on a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). The questionnaire assessed seven TPCK components, including Content Knowledge (CK), Pedagogical Knowledge (PK), Technological Knowledge (TK), Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and integrated Technological Pedagogical Content Knowledge (TPCK). To ensure content validity, the questionnaire was reviewed by five experts in Science Education, Curriculum and Instruction, STEM Education, and Technology Education. The Item-Objective Congruence (IOC) values ranged from 0.67 to 1.00, indicating acceptable content validity. The internal consistency reliability of the instrument was examined using Cronbach's alpha coefficient, which yielded an overall reliability value of  $\alpha = 0.92$ , demonstrating high reliability.

Example questionnaire items include:

"I can integrate appropriate technological tools to support students' understanding of scientific concepts."

"I can select technological tools that effectively support students' learning of subject-specific content."

"I can design learning activities that integrate subject content, technology, and instructional strategies to enhance students' learning."

The questionnaire was administered after the completion of the Engineering Design-Based STEM instructional intervention in order to assess participants' perceived development of TPCK following their engagement in STEM design activities.

### **3.4 Data Analysis**

Data analysis consisted of both qualitative and quantitative procedures in order to examine patterns of interdisciplinary integration and the development of Technological Pedagogical Content Knowledge (TPCK).

#### **Qualitative Data Analysis**

Qualitative data obtained from STEM design documentation, classroom observations, reflective journals, focus group interviews, and researcher field notes were analyzed using thematic analysis guided by the TPCK framework and the Engineering Design Process (EDP). The analysis followed three iterative stages:

1. Open Coding – identifying emerging patterns related to interdisciplinary integration, technological decision-making, and pedagogical reasoning during STEM design activities.

2. Axial Coding – grouping related codes into broader categories representing patterns of interdisciplinary coordination across STEM domains.



3. Selective Coding – synthesizing the categories to develop key themes explaining how Engineering Design-Based on STEM activities, supported TPCK development.

To enhance the credibility of qualitative findings, data triangulation was conducted by comparing multiple sources of evidence, including STEM design documentation, classroom observations, reflective journals, and interview transcripts. In addition, member checking was conducted during focus group discussions to confirm the accuracy of interpretations and ensure that the findings reflected participants' experiences.

### **Quantitative Data Analysis**

Quantitative data obtained from the TPCK self-assessment questionnaire were analyzed using descriptive statistics, including mean (M) and standard deviation (S.D.), to determine the level of TPCK development among participants following the Engineering Design-Based STEM instructional intervention. The statistical analysis was conducted using SPSS Statistics.

The interpretation criteria for TPCK development levels were defined as follows:

4.50 – 5.00: The development of TPCK for STEM integration is at the highest level.

3.50 – 4.49: The development of TPCK for STEM integration is at a high level.

2.50 – 3.49: The development of TPCK for STEM integration is at a moderate level.

1.50 – 2.49: The development of TPCK for STEM integration is at a low level.

Finally, qualitative and quantitative findings were integrated during the interpretation stage to provide a comprehensive explanation of how Engineering Design-Based STEM learning experiences contributed to the development of TPCK among second-year elementary student teachers.

## **4. Results and Discussion**

### **4.1 Engineering Design-Based STEM activities foster interdisciplinary integration across science, technology, engineering, and mathematics**

#### **4.1.1 Concept-Driven Design Constraints as Integrative Catalysts**

Across all four cases, integration was initiated through clearly defined design problems that imposed conceptual constraints. These constraints required participants to mobilize scientific principles and mathematical reasoning as functional tools for solving engineering challenges. For example, in the Projectile Launcher (Elastic Energy Application) case, students could not determine launch distance without understanding elastic potential energy, Newton's laws of motion, and projectile trajectories. Angle measurement and proportional lever construction required mathematical reasoning, while fulcrum placement and structural stability demanded engineering judgment. Similarly, in the Wind-Powered Car project, optimization of wheel rotation and sail positioning required coordinated understanding of wind force, friction, motion, and ratio relationships. Importantly, scientific and mathematical knowledge did not operate independently. Instead, disciplinary ideas became operational only when applied within material design constraints.

Classroom observations indicated that integration was most evident when students confronted material performance limitations. During the Projectile Launcher activity, one group initially constructed a lever system without calculating the projectile angle. When the prototype failed to reach the target distance, students revisited Newton's second law and angle trajectory relationships. A student remarked during redesign:

"We thought pulling harder would make it go farther, but the angle changed everything. We had to calculate the angle before changing the force."

"At first, we divided science and math separately. But when testing failed, we realized math helped explain why the science idea did not work."

Another student wrote:

"Design made us think how knowledge connects. If we changed one part, everything else changed."

These reflections suggest that integration was not pre-planned but emerged through iterative cognitive restructuring prompted by design instability.

In post-implementation focus groups, participants emphasized how engineering constraints forced disciplinary synthesis:

"In normal lessons, we study physics or math separately. But here, if we didn't combine them, the prototype simply didn't work."

Another participant noted:

"The design made the subjects depend on each other."

The author's field notes recorded:

Students shifted from trial-and-error adjustments to mathematically reasoned modifications after repeated failed launches. Integration became visible only after performance failure required a conceptual explanation.

Similarly, in the Wind-Powered Car case, students initially focused on sail size rather than friction reduction. Testing revealed that wheel resistance limited movement despite strong wind exposure. One group recalculated axle alignment and adjusted wheel symmetry after recognizing frictional force as a limiting factor. This supports the argument that engineering design provides a functional context in which disciplinary knowledge becomes epistemically integrated rather than thematically aligned. These findings suggest that interdisciplinary integration was not the result of simultaneous inclusion of STEM subjects, but rather the consequence of design problems that structurally required coordinated reasoning.

#### **4.1.2 Iterative Engineering Cycles as a Structural Organizer**

The Engineering Design Process (EDP) served as the central organizer of interdisciplinary integration. Each project followed six stages: problem identification, information gathering, solution design, implementation, testing and refinement, and presentation. This structured progression distributed cognitive demand across phases and required repeated negotiation between conceptual understanding and material performance. For instance, during the Eco-Water Turbine project, initial designs often failed to rotate efficiently. Testing revealed imbalances in blade symmetry and



insufficient torque generation. Students revisited energy transformation principles (kinetic to mechanical energy), reconsidered blade angle geometry, and modified structural components. Through these iterative refinements, scientific explanation, mathematical calculation, and engineering adjustment became tightly coupled. The iterative nature of EDP required students to move beyond single-discipline reasoning. Testing outcomes exposed conceptual weaknesses, prompting deeper engagement with underlying principles. Thus, the EDP did not merely sequence instructional activities; it functioned as a cognitive scaffold that compelled interdisciplinary synthesis. Observational data indicate that the Engineering Design Process functioned as a cognitive organizer that distributed reasoning demands across phases.

STEM activity Observations during the Eco-Water Turbine case, early prototypes rotated inconsistently, students analyzed blade angle symmetry and water flow resistance. One group used slow-motion video recording to examine rotational imbalance. The author's field notes documented:

Students began articulating cause-and-effect explanations linking blade geometry, torque generation, and water resistance. Mathematical symmetry calculations were used to justify redesign decisions. Repeated cycles of testing and refinement required students to revisit scientific explanations while adjusting structural design.

Reflective Journal Evidence, a participant reflected:

"Testing showed our science idea was incomplete. We had to re-learn energy transfer before redesigning the blades."

Another wrote:

"Each step of EDP made us think differently—first problem, then idea, then testing. It helped organize our thinking."

These reflections demonstrate that EDP functioned not merely as a procedural sequence but as an epistemic scaffold supporting integrative reasoning. This aligns with research suggesting that engineering design mediates conceptual integration by embedding disciplinary reasoning within cycles of experimentation and optimization.

#### **4.1.3 Technology as an Epistemic Instrument**

Across all four cases, technology was positioned as a tool for inquiry and evaluation rather than as a presentation medium. Students used measuring devices, digital timers, angle measurement tools, and observational recording systems to collect performance data and evaluate design efficiency. In the Wind Direction Indicator case, students refined pivot mechanisms after testing revealed instability under varying airflow conditions. Mathematical balance calculations and geometric symmetry informed adjustments. Technology supported measurement accuracy and documentation rather than decorative enhancement. This functional use of technology strengthened the integration between technological decision-making and disciplinary reasoning. Rather than applying technology superficially, participants were required to justify technological choices based on conceptual necessity. This pattern reflects deeper interdisciplinary alignment, where technological affordances support scientific and mathematical analysis within

engineering constraints. Across all cases, technology was primarily used for measurement, testing, and performance analysis rather than for presentation.

Field Observation Evidence, in the Wind Direction Indicator project, groups used digital angle measurement tools to confirm rotational alignment. Students adjusted the pivot balance after observing deviation from true north under moderate airflow conditions. The author recorded:

Technology was consistently used to verify performance accuracy. No group used digital slides or decorative presentation tools during testing phases. Similarly, in the Projectile Launcher activity, students used digital timers and measurement tapes to compare launch distances across trials. Data were recorded and graphed to determine optimal angle-force combinations. Focus Group Evidence, students articulated a shift in their perception of technology:

“Before this course, we thought technology meant PowerPoint. Now we see it as a tool to measure and test.”  
 Another participant reflected:

“Technology helped us understand our design, not just explain it.”

This shift suggests movement toward functional technological integration consistent with TCK development.

#### 4.2 Development of TPCK Components Following Engineering Design-Based STEM Implementation

Quantitative analysis was conducted to examine the development of Technological Pedagogical Content Knowledge (TPCK) among second-year elementary student teachers following their participation in Engineering Design-Based STEM learning activities. The results of the descriptive statistical analysis are presented in Table 1.

**Table 1** Mean and Standard Deviation of TPCK Components Following Engineering Design-Based STEM Integration  
 (n = 30)

| TPCK Components                                    | M    | S.D. | Level | Rank |
|----------------------------------------------------|------|------|-------|------|
| Content Knowledge (CK)                             | 4.22 | 0.51 | High  | 7    |
| Pedagogical Knowledge (PK)                         | 4.25 | 0.52 | High  | 5    |
| Technological Knowledge (TK)                       | 4.34 | 0.59 | High  | 2    |
| Pedagogical Content Knowledge (PCK)                | 4.40 | 0.59 | High  | 1    |
| Technological Content Knowledge (TCK)              | 4.33 | 0.61 | High  | 4    |
| Technological Pedagogical Knowledge (TPK)          | 4.33 | 0.60 | High  | 3    |
| Technological Pedagogical Content Knowledge (TPCK) | 4.23 | 0.62 | High  | 6    |
| Overall                                            | 4.29 | 0.58 | High  |      |

The overall level of TPCK development was found to be high ( $M = 4.29$ ,  $S.D. = 0.58$ ), indicating that participation in Engineering Design-Based STEM activities contributed positively to preservice teachers' perceived competence in integrating content knowledge, pedagogy, and technology.

Among the seven TPCK components, Pedagogical Content Knowledge (PCK) demonstrated the highest mean score ( $M = 4.40$ ,  $S.D. = 0.59$ ), ranking first. This result suggests that the STEM design activities particularly supported participants' ability to transform disciplinary knowledge into meaningful learning experiences for students.

The second-highest mean score was observed for Technological Knowledge (TK) ( $M = 4.34$ ,  $S.D. = 0.59$ ), followed by Technological Pedagogical Knowledge (TPK) ( $M = 4.33$ ,  $S.D. = 0.60$ ) and Technological Content Knowledge (TCK) ( $M = 4.33$ ,  $S.D. = 0.61$ ). These findings indicate that the use of technological tools during STEM design activities supported the development of participants' ability to integrate technology with both pedagogical strategies and subject content. In addition, Pedagogical Knowledge (PK) showed a high level ( $M = 4.25$ ,  $S.D. = 0.52$ ), suggesting that participants developed stronger instructional strategies for facilitating student learning during STEM activities.

Although the integrated TPCK component also reached a high level ( $M = 4.23$ ,  $S.D. = 0.62$ ), it ranked sixth among the seven components. This finding suggests that while participants demonstrated strong development in individual knowledge domains and their intersections, the full integration of content knowledge, pedagogy, and technology remained a complex competency that requires continued professional development. Finally, Content Knowledge (CK) showed the lowest mean score ( $M = 4.22$ ,  $S.D. = 0.51$ ), ranking seventh among the components. Nevertheless, the score still indicates a high level of perceived competence.

Overall, these results suggest that Engineering Design-Based STEM learning activities supported the development of multiple dimensions of TPCK, particularly in relation to pedagogical transformation of disciplinary knowledge and the meaningful use of technological tools in STEM learning environments.

## 4.2 Discussion

The findings of this study indicate that Engineering Design-Based STEM activities can serve as an effective instructional framework for fostering interdisciplinary integration and supporting the development of Technological Pedagogical Content Knowledge (TPCK) among preservice teachers. Rather than emerging from the simple coexistence of multiple STEM disciplines, integration in this study was driven by design constraints that required coordinated reasoning across scientific, mathematical, technological, and engineering domains. This observation aligns with recent research emphasizing that meaningful STEM integration occurs when learners engage in problem-centered design tasks that require cross-disciplinary reasoning (Thibaut et al., 2020; Dare et al., 2021).

A key mechanism supporting interdisciplinary integration was the Engineering Design Process (EDP), which functioned as a mediating epistemic scaffold. Through iterative cycles of problem identification, solution design, testing, and refinement, student teachers were required to revisit disciplinary concepts and refine their design strategies based on empirical evidence. This iterative structure encouraged deeper conceptual engagement and promoted the

coordination of disciplinary reasoning. These findings support previous studies suggesting that engineering design-based learning environments facilitate integrative thinking by embedding conceptual knowledge within authentic problem-solving contexts (Hynes et al., 2020; Pleasants & Olson, 2021).

The study also highlights the epistemic role of technology in STEM learning environments. Rather than being used primarily as a presentation tool, technology in this study supported measurement, testing, and analysis during the design process. Such functional use of technology reflects the principles of meaningful technology integration emphasized in the TPCK framework, where technological tools are selected based on their ability to support conceptual understanding and inquiry processes (Schmid et al., 2021; Koh et al., 2022). This finding suggests that design-based STEM activities may provide valuable opportunities for preservice teachers to develop Technological Content Knowledge (TCK) and Technological Pedagogical Knowledge (TPK) through authentic practice.

The quantitative findings further support the qualitative observations regarding TPCK development. All TPCK components were reported at a high level, with Pedagogical Content Knowledge (PCK) demonstrating the highest mean score. This pattern suggests that participation in design-based STEM activities enhanced preservice teachers' ability to transform disciplinary knowledge into meaningful instructional tasks. Previous research has similarly indicated that design-oriented teacher education experiences strengthen pedagogical reasoning and support the development of student-centered instructional strategies (Radloff & Guzey, 2021; Dare et al., 2023).

However, the comparatively lower ranking of the fully integrated TPCK component suggests that the simultaneous coordination of content knowledge, pedagogy, and technology remains a complex professional competency. This finding is consistent with longitudinal studies indicating that integrative professional knowledge develops progressively and often requires sustained practice across multiple teaching contexts (Chai et al., 2021; Voogt et al., 2023). Consequently, teacher education programs may need to provide continued opportunities for preservice teachers to engage in interdisciplinary STEM design experiences in order to strengthen their integrative teaching competence.

Overall, the results suggest that Engineering Design-Based STEM learning environments provide a powerful pedagogical context for developing integrative professional knowledge among preservice teachers. By embedding disciplinary concepts within authentic design challenges, such learning environments encourage preservice teachers to coordinate content knowledge, technological tools, and pedagogical strategies in meaningful ways. These findings contribute to the growing body of research highlighting the potential of design-based STEM education as a mechanism for advancing TPCK development in teacher education programs.

## 5. Conclusion

This study examined how Engineering Design-Based STEM activities foster interdisciplinary integration and support the development of Technological Pedagogical Content Knowledge (TPCK) among second-year elementary student teachers. The findings provide convergent qualitative and quantitative evidence that structured design-based STEM experiences create authentic and epistemically rich conditions for integrative professional learning. The results



demonstrate that interdisciplinary integration does not arise from thematic alignment of STEM subjects, but from structurally mediated design constraints that require coordinated reasoning across domains. Engineering challenges compelled student teachers to mobilize scientific principles, mathematical evaluation, technological tools, and engineering judgment within iterative cycles of testing and refinement. The Engineering Design Process (EDP) functioned as both a cognitive and epistemic scaffold, distributing conceptual demand, exposing disciplinary limitations, and promoting cross-domain reconciliation. Integration, therefore, emerged as a performance-driven necessity embedded within material problem-solving rather than as a superficial curricular arrangement.

Furthermore, the implementation of Engineering Design-Based STEM activities contributed positively to TPCK development. All TPCK components reached high levels, with particularly strong gains observed in Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK). These findings suggest that when technology is embedded within authentic design tasks, it becomes epistemically aligned with disciplinary reasoning and pedagogical decision-making. At the same time, the comparatively lower ranking of fully integrated TPCK underscores the developmental complexity of simultaneously coordinating content, pedagogy, and technology. Integrative professional expertise appears to evolve progressively through iterative enactment rather than immediate exposure. Theoretically, this study advances TPCK scholarship by demonstrating that integrative competence develops through structured design enactment under authentic constraints. Engineering Design-Based STEM activities provide a mediating environment in which knowledge domains are not accumulated independently but continuously negotiated through contextualized performance demands. Practically, the findings highlight the importance of embedding student teachers in structured, problem-driven STEM design experiences early in their preparation. When teacher education programs move beyond lecture-dominant models and create iterative, design-centered learning environments, interdisciplinary integration and TPCK development become enacted professional competencies rather than abstract theoretical constructs.

In conclusion, Engineering Design-Based STEM instruction offers a coherent and theoretically grounded pedagogical mechanism for cultivating interdisciplinary integration and advancing integrative professional expertise in elementary teacher education.

## 6. Recommendations

The findings suggest that teacher education programs should systematically integrate Engineering Design-Based STEM activities into a Learning Management in Science for Elementary School Teachers course to strengthen interdisciplinary integration and TPCK development. Structured design cycles, when combined with guided reflection and collaborative problem-solving, provide meaningful opportunities for student teachers to coordinate content knowledge, pedagogical reasoning, and technological application within authentic contexts. Teacher educators should also emphasize the use of technology as an epistemic tool for inquiry, measurement, and design optimization rather than as a presentation medium.

For future research, longitudinal studies are recommended to examine the sustained development of integrative TPCK over time. Comparative research exploring different STEM instructional models may further clarify the unique contribution of Engineering Design-based approaches. Additionally, studies investigating how TPCK development translates into enacted classroom practice would provide valuable insight into the long-term impact of design-based STEM experiences in teacher education.

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