IJRES International Journal of Research in Education and Science

www.ijres.net

Investigating the Pedagogical Content Knowledge for Navigating Through Integrated STEM Education Spaces: The Case for Robotics Teaching

Christopher Mutseekwa [1*], Pinius Chikuvadze [2]

[1] University of Rwanda-College of Education Laboratory School, Rwanda, 0000-0002-2070-9952
[2] University of the Free State, South Africa, 0000-0002-8569-0009
* Corresponding author: Christopher Mutseekwa (chrismutseekwa@gmail.com)

Article Info

Article History

Received:
13 August 2025

Revised:
20 November 2025

Accepted:
7 December 2025

Published:
1 March 2026

Keywords

Contextualized curricular knowledge
Design-based engineering
Educational robotics
Marine ecosystems
Programming algorithms

Abstract

Since the conception of pedagogical content knowledge (PCK) in the 1980s, the majority of research on PCK has focused on particular subjects, chemistry, physics, mathematics, and others, with fewer studies shedding light on the nature of PCK needed for integrated STEM (iSTEM) education. This study investigates the development of PCK among early career teachers tasked to introduce robotics to secondary school learners. An exploratory case study within the interpretive paradigm was employed to investigate teachers' pedagogical content knowledge for navigating through the educational robotics curriculum in a model school in Rwanda. Three STEM teachers and nine students were conveniently selected to constitute a team that represented the school in a district robotics competition. Data was generated through observations, semi-structured interviews, and document study. Content analysis is employed to generate themes and ordinal categories that are used to report the findings. The findings revealed that the Education Robotics trainers' application of composite STEM-PCK ranged from low to moderate. On one hand, the educators demonstrated limitations regarding the contextualization of curricular knowledge to align with local environments, while on the other, applying cross-disciplinary pedagogical knowledge and technological integration knowledge moderately. The study concluded that an iSTEM-PCK demanded shifts from being teachers to facilitators who possess knowledge of engineering design, project-based learning, and the capabilities to steer self-regulated learning.

Citation: Mutseekwa, C. & Chikuvadze, P. (2026). Investigating the pedagogical content knowledge for navigating through integrated STEM education spaces: The case for robotics teaching. *International Journal of Research in Education and Science (IJRES), 12*(2), 479-496. https://doi.org/10.46328/ijres.5457

Introduction

The concept of pedagogical content knowledge (PCK) is widely recognized as essential for effective teaching and learning within the science, technology, engineering, and mathematics (STEM) disciplines (Yip, 2025). PCK represents the specialized knowledge that enables educators to deliver specific content in practical and impactful ways. The recent advancements in science and technology education, which have spurred reforms in interdisciplinary STEM initiatives, necessitate the development of innovative forms of PCK to align with these evolving pedagogical demands. The challenges and complexities faced by novice teachers in their early careers, coupled with new teaching requirements, have intensified the already significant rates of attrition and turnover within the profession, thereby heightening the importance of STEM PCK (Tsarkos, 2024). Since Shulman's (1986) initial framing of PCK, research has predominantly concentrated on specific subject areas, such as biology, chemistry, physics, and mathematics, with comparatively limited investigation into the nature of PCK necessary for integrated STEM (iSTEM) education, such as robotics. PCK is understood as a domain-specific knowledge related to teaching, encompassing what educators know about their subject matter and how to render it comprehensible to students (Schneider & Plasman, 2011). Research in science, mathematics, and technology education posits PCK as the result of accumulated experiences, refined through reflective practices regarding students, considering their learning preferences, worldviews, teaching methodologies, curriculum, assessment strategies, and the learning environment itself.

For science teachers to effectively develop PCK, a deep understanding of scientific principles, general pedagogical theories, and the contextual factors related to their students and educational settings is essential. This specialized knowledge helps educators improve students' engagement and understanding in science. Although there is broad discussion about specialized teaching knowledge, ongoing research into the nature and development of PCK for teachers at different career stages and in diverse STEM teaching environments remains important (Abell, 2008). Traditional approaches to STEM education, while foundational, are being reconsidered given the fast-changing educational landscape and the needs of a globally competitive society (Council, 2011). Recent progress in STEM education has shifted toward more student-centered, hands-on learning methods (Keiler, 2018). Project-based learning (PBL) has become an active strategy, giving students chances to apply theoretical knowledge in real-world situations. Interdisciplinary approaches break away from the isolated nature of traditional STEM education (Al Hamad et al., 2024). Students learn about the connections among scientific principles, technological tools, engineering design, and mathematical reasoning by combining multiple disciplines. This integrated approach reflects the teamwork needed to solve real-world problems and boosts students' ability to transfer knowledge across different areas.

The integration of technology has significantly transformed the landscape of STEM education, transcending traditional pedagogical methodologies (Crippen & Archambault, 2012). The deployment of digital resources, virtual laboratories, and online tools has facilitated greater accessibility to STEM learning, effectively mitigating geographical constraints and providing students with engaging, multimedia-enhanced educational experiences. Within this context, the role of Educational Robotics (ER) as a catalyst for integrated STEM (iSTEM) education has garnered substantial recognition in scholarly discourse (Ortiz et al., 2015). Specifically, tools such as the Bee-

Bot have been identified as effective means for fostering Computational Thinking, a critical skill encompassing problem-solving and the representation of solutions executable by both humans and machines, grounded in principles of computer science (Alam & Mohanty, 2024; Ponticorvo et al., 2022). Additionally, Moraiti et al. (2022) elucidate the notable shift in educational paradigms during the 21st century, marked by an increasing convergence of technology and pedagogical techniques. Within this evolving framework, the advent of robotics technology has engendered transformative opportunities in educational settings, facilitating the establishment of a dynamic platform that transcends conventional subject boundaries (Demetroulis et al., 2023). These shifts in the STEM education landscape necessitate reimagining the PCK concept to align it with contemporary demands in iSTEM teaching.

This study investigates the experiences and development of pedagogical content knowledge (PCK) among early career teachers tasked to introduce robotics to secondary school learners. It highlights the teachers' challenges and innovations as they grapple with pedagogical strategies needed for facilitating iSTEM learning in a robotics curriculum. Specifically, the study sought answers to the following questions:

(1) How do teachers integrate disciplinary content knowledge in STEM when teaching robotics in secondary school settings?
(2) What pedagogical strategies do teachers use to navigate cross-disciplinary and technological integration challenges in robotics teaching?
(3) How do teachers contextualize robotics curricula and support students' epistemic engagement in integrated STEM learning environments?

A Conceptual Framework for Integrated STEM Teaching

Lee Shulman (1986) introduced the concept of Pedagogical Content Knowledge (PCK) to explain how educators transform their subject matter knowledge and pedagogical skills into understandable and teachable formats for students. In Shulman's framework, traditional PCK is defined as discipline-specific (e.g., science PCK, mathematics PCK), contextualized (influenced by teachers' experiences, student needs, curricula, and assessments), and integrated (covering content knowledge (CK), pedagogical knowledge (PK), as well as understanding students and their contexts). However, the model of integrated STEM teaching goes beyond the conventional limits of separate disciplines and encourages solving real-world problems by applying knowledge and methods from science, technology, engineering, and mathematics (Ponticorvo et al., 2022). This approach reflects transdisciplinary thinking, where the boundaries between subjects become flexible (Burnard & Colucci-Gray, 2021), and involves designing authentic tasks that require integrating multiple knowledge areas (Lowell & Moore, 2020). Such integration presents significant challenges to traditional PCK models in several important ways. First, teachers must effectively manage different knowledge bases, focusing not only on content but also on how students learn that content. This includes creating opportunities for active learning, aligning the curriculum with teachers' knowledge and beliefs, understanding learning theories, recognizing students' preferred learning styles, and using transdisciplinary and multidisciplinary teaching approaches (Rodriguez, 2013). Second, educators need to understand the relationships among concepts from various disciplines and adopt flexible teaching strategies to support effective cross-disciplinary learning and design-based tasks. To meet these complex challenges, this study proposes the development of the ‘Composite STEM-PCK’ framework.

The Composite STEM-PCK Conceptual Model

In the context of this study, composite STEM-PCK is the specialized, integrative knowledge that STEM teachers develop to effectively design and facilitate learning experiences that blend content, pedagogy, and epistemologies across multiple STEM disciplines. It is not the sum of individual disciplinary PCKs, but a synthesized, emergent knowledge base suited for interdisciplinary problem-solving and design. While the term "composite STEM-PCK" might be novel, related ideas already exist, showing scholarly precedent. Thus, the Composite STEM-PCK model draws inspiration from the TPACK that adds technological fluency to content and pedagogy (Mishra & Koehler, 2006), the Interdisciplinary Knowledge Integration that endeavors to understand how to connect concepts, methods, and epistemologies across domains (Mansilla, 2006), Epistemic Fluency, assessing teachers’ ability to work across and combine different ways of knowing (Markauskaite & Goodyear, 2016), and the Boundary Crossing Theory that frames how teachers navigate and integrate between disciplinary knowledge systems (Akkerman & Bakker, 2011). The suggested key integrative components of the Composite STEM-PCK model are shown in Table 1.

Table 1. Key integrative components of the ‘Composite STEM-PCK model’ (Source: Authors’ own elaboration)

Component(s)	Description	Illustration
Integrated Content Knowledge (ICK)	Understanding how concepts from science, mathematics, engineering, and technology interrelate.	Using Newton's laws (science) to analyze forces in a bridge (engineering) and model them mathematically.
Cross-disciplinary Pedagogical Knowledge (CPK)	Knowing how to design learning activities that involve inquiry, modeling, design thinking, coding, etc.	Using PBL (problem-based learning) to solve a STEM challenge.
Contextualized Curricular Knowledge (CCK)	Understanding curriculum standards, real-world applications, and project constraints across disciplines.	Designing a unit that aligns with both math and science standards while incorporating design processes.
Technological Integration Knowledge (TIK)	Ability to incorporate tools (e.g., simulations, data loggers, CAD software) across domains.	Aligned with TPACK but viewed as an enabler of STEM integration.
Epistemic Integration Knowledge (EIK)	Awareness of and ability to navigate different ways of knowing (e.g., empirical science vs. design-based engineering).	Assists teachers in resolving epistemological tensions in interdisciplinary teaching.

Table 1 presents ICK, CPK, CCK, TIK, and EIK as the five components of the Composite STEM-PCK model. This integrative approach emphasizes a synthesized form of pedagogical content knowledge (PCK) that draws from multiple disciplines, providing a framework tailored to integrated STEM education. This framework underscores the necessity for synthesis rather than the mere aggregation of disciplinary PCKs. The Composite STEM-PCK model exhibits several characteristics that contribute to its conceptual robustness and scientific plausibility.

Firstly, it embodies cognitive coherence across disciplines, emphasizing the interconnectedness of knowledge. Nathan et al. (2013) assert that educators require cognitive coherence and not merely a mastery of mathematics, science, or engineering in isolation, but an understanding of how to teach at their intersections. This includes employing mathematics to model scientific data within engineering contexts. Such activities that foster cohesion facilitate student comprehension by linking conceptual relationships across various mathematical representations, scientific principles, technological resources, engineering designs, educational environments, and societal constructs (Nathan et al., 2013).

Secondly, the model advocates for pedagogical pluralism, which is defined as the integration of diverse teaching methodologies and strategies within a learning environment (Obeng-Odoom, 2019). Effective STEM integration often necessitates a variety of pedagogical approaches, including inquiry-based learning (science), modeling (mathematics), design-based thinking (engineering), and coding (technology) (Subramaniam et al., 2025). The recognition of pedagogical plurality within a composite PCK is essential for fostering a dynamic learning experience.

Lastly, the proposed Composite STEM-PCK model harnesses cross-disciplinary knowledge to enhance problem-solving capabilities. A STEM-integrated task may require a confluence of scientific knowledge (e.g., energy concepts), mathematical skills (e.g., data graphing), engineering design principles (e.g., prototype construction), and technological tools (e.g., simulation software). Thus, a composite PCK equips educators to design and deliver instruction that interweaves these elements coherently, promoting meaningful learning experiences for students.

Literature Review

In the academic discourse surrounding pedagogical practices, the concept of Pedagogical Content Knowledge (PCK) is recognized as the specialized knowledge that educators possess regarding the effective instruction of specific material or subject matter (Hartelt et al., 2022). This construct encompasses three interrelated dimensions of expertise: Pedagogical Knowledge (PK), Content Knowledge (CK), and PCK itself. According to Wells et al. (2023), PK refers to the proficiency in selecting and implementing appropriate teaching strategies, crafting lesson plans, understanding student needs, and managing the classroom environment. CK, as defined by Padalkar et al. (2022), involves a comprehensive understanding of fundamental concepts, theories, principles, and factual information within the domain of natural science knowledge, particularly for prospective science educators. PCK represents a synthesis of pedagogical and content knowledge, resulting in a nuanced comprehension of how to effectively teach specific content areas (Tyas et al., 2025). Moreover, Tyas et al. (2025) suggest that the conception of PCK is progressively evolving towards Technological Pedagogical Content Knowledge (TPACK). This transition is largely influenced by the global technological advancements associated with the Industrial Revolution 5.0 (IR 5.0), which necessitates that STEM educators adapt to contemporary educational paradigms. However, a significant number of teachers currently lack the requisite technological expertise in instructional environments, resulting in an inadequate development of PCK suitable for the IR 5.0 context.

In a relevant study conducted by Ong and Annamalai (2024), the focus was on the cultivation of Technological Pedagogical Content Knowledge for twenty-first-century learning skills (TPACK21cls) within the structured, implemented, and experiential dimensions of a teaching curriculum aimed at the Teaching of English as a Second Language in an Institute of Teacher Education in Malaysia. Their research findings indicated that, while there was a pronounced emphasis on Content Knowledge and Pedagogical Content Knowledge within the planned curriculum, TPACK21cls was not explicitly integrated into the delivery of the curriculum. Ong and Annamalai (2024) present a research study that, while primarily directed towards English language educators, offers significant insights pertinent to the advancement of STEM Pedagogical Content Knowledge (PCK). STEM educators encounter the imperative challenge of adapting to the swift pace of technological innovations, an expanding array of educational and training tools, and the evolving processes of communication among adolescents as they navigate a rapidly transforming societal and cultural landscape (Thyssen et al., 2023). Thyssen et al. (2023) argue that addressing contemporary challenges requires a shift from a predominant focus on Technological Pedagogical Content Knowledge (TPACK) to Digital Pedagogical Content Knowledge (DPACK), emphasizing the critical role of "digitality" in effective 21st-century STEM instruction. The authors assert that the digital transformation of STEM education requires an enhanced professional knowledge base that is responsive to the evolving dynamics of communication, media influence, and societal change. Furthermore, it is essential to equip children and adolescents within this digitally influenced milieu with the skills to evaluate and ethically engage in these transformative processes critically.

At the forefront of ‘digitality’ lies Educational Robotics (ER). ER offers a robust and comprehensive problem-solving space that enables students to put STEM concepts into practice. (Hussain et al., 2006). However, there is limited research on the pedagogical content knowledge (PCK) necessary for facilitating ER. Among the few studies available, Hsu and Tsai (2024) examined the relationships between preservice and in-service teachers' computational thinking (CT), design thinking (DT), their beliefs about teaching robotics, and their robotics pedagogical content knowledge (RPCK). The findings indicated that both CT and DT attitudes positively influenced teachers’ beliefs about robotics teaching, which in turn affected their RPCK. Additionally, a direct positive link between CT and RPCK was established, whereas such a link was absent for DT. Computational thinking (CT) encompasses a range of concepts, practices, and perspectives that facilitate problem-solving, particularly in computer science. It involves dissecting complex problems into smaller, manageable components and applying algorithmic reasoning to resolve them (Wing, 2006; Yang et al., 2024).

In another study, Yang (2025) implemented a professional development (PD) program that integrated technologies, pedagogies, and computational thinking to improve the pedagogical knowledge of Early Childhood Education (ECE) teachers. The outcomes showed that this program significantly enhanced the teachers' knowledge of robotics and pedagogy, as well as their attitudes toward computational thinking, particularly in terms of their interest and perceptions regarding its application in classroom settings (Yang, 2025). Similarly, Cepni et al. (2024) conducted a comprehensive study in which they developed a scaffolded professional development (PD) program that encompassed an introductory overview of robotics, task assignments grounded in the P3 Task Taxonomy, and lesson planning that synergistically integrated principles from science, mathematics, and robotics. The P3 Task Taxonomy consists of three distinct components: a practice segment characterized by close-ended tasks, a problem-solving section featuring open-ended tasks, and a project segment that poses a complex, driving question. Utilizing a paired-sample t-test for analysis, Cepni et al. (2024) revealed that the P3 Task Taxonomy scaffolded PD program yielded significant advancements with large effect sizes in the domains of robotics (2.08), science (1.49), and mathematics (0.92). These findings bear substantial implications, suggesting that the P3 Task Taxonomy represents an innovative methodology that transcends traditional approaches in facilitating professional development within educational robotics contexts.

Methods

Research Design

An exploratory case study within the interpretive paradigm was employed to investigate a contemporary phenomenon situated within its real-life context. The term "case study" is commonly understood to refer to the collection of comprehensive, somewhat unstructured information from diverse sources regarding a particular individual, group, or institution, frequently incorporating the perspectives of the subjects themselves (Bergen & While, 2000). An exploratory case study design was deemed appropriate for the investigation of STEM-PCK, given that this phenomenon remains inadequately defined and lacks a singular set of outcomes (Yin, 2003).

Participants and Data Collection

The study's participants included an Information Technology teacher, a Robotics expert tutor, and a Physics teacher, together with a team of nine students (five girls and four boys) who were conveniently selected to form a team representing a model school at a district robotics competition in the Eastern Province of Rwanda. Following the requirements for confidentiality, the teachers were codenamed ERT 1, 2, and 3, respectively. Data were collected through observations, document analysis, and semi-structured interviews. The observation was largely non-participatory. A total of 13 sessions were observed, running through the course of three months. The notes found in the teachers' preparation plans, the regular reports they made on training progress, assessment rubrics used in mock competitions, and the students' draft notes scribbled during training sessions were part of the documents that were analyzed.

Following Adeoye-Olatunde and Olenik's (2021) assertions, semi-structured interviews with the three trainers allowed for both consistency across participants and flexibility to explore interesting topics. These interviews were conducted after the district competitions, which marked the end of the season's activities. To cover all three research questions, here are examples of questions that were asked in the interviews: Can you describe a recent robotics lesson or project where multiple STEM disciplines were integrated? How do you ensure students understand the disciplinary concepts embedded in the robotics tasks? How do you support students who are stronger in one area (e.g., coding) but weaker in others (e.g., math)? How do you adapt your robotics lessons to your students' interests or local context? What kinds of activities promote deeper thinking, questioning, or collaborative problem-solving? How do you foster students' sense of ownership and inquiry within your team?

Data Analysis

The qualitative data collected from both observations and document analyses were systematically utilized to generate comprehensive field notes. The recorded interviews underwent transcription by the second researcher, after which both researchers engaged in a thorough analysis of the data from the triangulated approaches. Content analysis was employed following Bengtsson's (2016) four stages: decontextualization (identifying meaning units), recontextualization (retaining relevant content while excluding extraneous material), categorization (forming homogeneous groups), and compilation (drawing informed conclusions). The data processed by the two researchers was integrated during the third stage to condense the meaning units, thereby facilitating investigator triangulation.

During the compilation phase of this study, we drew conclusions regarding (1) the thematic elements and (2) the levels of Pedagogical Content Knowledge (PCK) application across the five components of the Composite STEM-PCK model (refer to Table 1). To facilitate this analysis, we utilized both manifest (surface-level meanings) and latent (underlying meanings) analytical frameworks, as outlined by Bengtsson (2016). This approach enabled us to categorize the data into three ordinal classifications: PCK significantly applied, PCK moderately applied, and PCK not applied, as detailed in the analytical rubric presented in the Appendix attached. Thus, findings were articulated through thematic representation, assigned categories, and supporting quotes. Furthermore, adherence to Clause 9 of the school's rules and regulations charter, which permits the use of photographs, recordings, and video imagery captured during school activities—both within and outside the classroom—for scholarly publications and academic purposes, provided essential ethical guidelines for the study.

Findings and Discussion

This section presents the findings and discussion under three sub-headings- interdisciplinary content integration, cross-disciplinary pedagogical and technological integration, and contextualization and epistemic engagement. The sub-headings align with the study's research questions and the proposed study's conceptual model-Composite STEM-PCK model.

Interdisciplinary Content Integration

The findings indicated that teachers' prior experiences with individual STEM disciplines significantly influenced the development of their pedagogical content knowledge (PCK) for integrated STEM (iSTEM) teaching. Most participants were subject specialists, having been trained in either a single or double major within a specific STEM discipline, which also aligned with the subjects they taught in mainstream classrooms. Given this disciplinary background, many teachers expressed uncertainty about how to meaningfully integrate the various STEM elements present in robotics activities. Observations of the ER sessions further revealed that teachers exhibited hesitation when engaging with content that fell outside their areas of expertise. For instance, on one hand, the

Physics/Mathematics teacher was comfortable explaining the principles of sensors (e.g., how light sensors mimic photoreceptors in organisms). However, he hesitated when students asked how to code the robot to respond to changes in light, as this required understanding conditional statements (e.g., `if-else`) and loops in a programming language like Python or Scratch, which he had not been trained in. On the other hand, the Information Technology teacher was proficient in building and programming robots using LEGO Mindstorms, but when students began asking questions about the physics behind the robot's movement (e.g., friction, torque, or Newton's laws), the teacher was hesitant to address these questions, worrying about giving scientifically inaccurate explanations.

To confirm their hesitation, they would then call in the other colleague whom they thought was better acquainted. In the context of STEM teaching, this call for assistance was a positive step that reinforced the concept of "pool PCK," wherein teachers collaborate by leveraging their complementary strengths (Cepni et al., 2024). However, the challenge arose when students required support in areas that did not have representation among the participating teachers. The teachers lacked clear ideas on how they could ensure students understood the disciplinary concepts embedded in the robotics tasks. They often lacked a clear interdisciplinary strategy for integrating the STEM concepts within robotics activities. Instead of using the task as a platform to deepen conceptual understanding, they tended to focus on task completion (e.g., building or coding the robot to function) without explicitly connecting it to the underlying disciplinary knowledge. For instance, mathematical concepts were overlooked in robot navigation; engineering concepts were not explicitly discussed when making design choices; and programming concepts were sometimes treated as trial-and-error. In the first scenario, students were asked to program a robot to follow a square path, but the teachers only emphasized getting the robot to turn and move correctly, missing opportunities to discuss the mathematics behind the angles (e.g., 90° turns), distance calculations, or coordinate geometry. In the third scenario, instead of asking students to predict what a particular code would do before running it or to modify the program to meet new conditions, the teachers simply guided students to use block-based programming to control motors and sensors. In line with Hussein et al.'s (2006) observations, this approach, where the teacher only focuses on achieving the correct output, misses chances to explore programming logic, control flow (e.g., loops, conditionals), or debugging strategies.

Relating to the Integrated Content Knowledge (ICK) component of the Composite STEM-PCK model, data from the interviews were summarized as: *PCK Moderately Applied.* A moderate application of ICK was discerned from the interview data because one of the teachers showed indications of an awareness of this type of PCK, while the others manifested limitations in the component. To illustrate, when ERT 2 was asked how content knowledge could be integrated in an interdisciplinary manner, he responded:

> *As tutors, we need to ensure the learners link the task or mission in robotics to particular concepts from the different STEM areas. For example, we can teach speed or distance, even angles from mathematics, to match with the created codes, which is a programming language in the field of IT.*

The other two teachers largely showed their limitations in ICK by failing to scaffold interdisciplinary reasoning, struggling to design or adapt lessons to reflect overlapping concepts, and having difficulty in anticipating or addressing cross-disciplinary misconceptions. Asked how he would ensure interdisciplinary tasks integration in his ER session, ERT 1 said:

> *The experts from the Rwanda Basic Education Board who oriented us into this ER left a LEGO FIRST manual to guide us. The procedures in that manual can be very useful. That manual rarely refers to this topic of concepts or content integration. But where it fits I think it can be good, although I will stick to the procedures and of course my Information Technology content on programming.*

ERT 3 had this to say:

> *I find it challenging to address some of the issues with the learners because some of the concepts they fail to understand are not within my subject area. For example, you are aware that following this year's theme, 'submerged,' our learners chose to design a robot that removed barnacles from sea animals such as whales and turtles. As they tried to connect their project with climate change, they later faced challenges explaining concepts such as warming waters, thermal expansion, greenhouse emissions, ocean acidification, marine heatwaves, and coral bleaching. I could not help much because this is an area in biology, and our team did not have a biology specialist.*

The two teachers' sentiments demonstrated their fixation with the siloed specialization of subjects rather than integration. The teachers also showed a lack of the ICK needed to anticipate learners' misconceptions or to unpack them using concepts from multiple disciplines. Thus, this result confirmed Demetroulis et al.'s (2023) findings that the nature of teachers' support to the learners during ER sessions tended to be procedural rather than conceptual.

Cross-disciplinary Pedagogical and Technological Integration

This section delineates two critical components of the Composite STEM-PCK model: Cross-disciplinary Pedagogical Knowledge (CPK) and Technological Integration Knowledge (TIK), both categorized under a summary assessment of Pedagogical Content Knowledge (PCK), which was found to be moderately applied according to the analysis rubric (see Appendix). Notably, ERT 2 demonstrated superior performance relative to his counterparts in the CPK and TIK domains. In response to an inquiry regarding the elements that constitute pedagogical knowledge in ER, he articulated:

> *It is important that when we carry out ER sessions, we treat them the same way as lessons. It means we should prepare and have plans that state the goals, objectives, and activities to achieve them. Pedagogical knowledge on ER should include knowledge on the global challenges (e.g., climate change, health and wellness), familiarity with AI, ability to navigate different teaching approaches such as project-based learning, and how to link with real-world contexts.*

The discourse surrounding contemporary Educational Robotics (ER) increasingly highlights its intersection with Artificial Intelligence (AI), underscoring the symbiotic relationship between the two fields (Ong & Annamalai, 2024; Thyssen et al., 2023). ER is progressively incorporating AI technologies to enhance the learning experience, making it more interactive, adaptive, and realistic. Conversely, AI functionalities serve as tutors or personalized learning assistants, adeptly guiding students through lessons, identifying individual strengths and weaknesses, and customizing content delivery to meet diverse educational needs. However, an analysis of the interview data revealed certain limitations, particularly for ERT 1 and 3. These two exhibited deficiencies related to essential design principles such as balance, weight distribution, and gear ratios. Consequently, these shortcomings resulted in the development of ineffectively functioning robots and a failure to establish meaningful connections between programming logic and the corresponding real-world behaviors of the robots. Such observations underscore the need for refinement in the design principles to enhance the educational efficacy of ER initiatives (Hsu & Tsai, 2024). Asked how he supported students who were stronger in one area (e.g., coding) but weaker in others (e.g., math), ERT 3 said:

> *Our selection of students who join the ER team was targeted. We tried to select all-rounders. Those we thought were good in all the subjects. So if it so happens that we have one like that, I think I would ask his or her peers to help him in the weaker area.*

Although ERT 3's sentiment showed that he had an idea, he failed to identify additional approaches such as the application of coding to solve real mathematics problems, the use of visuals and simulations, and rotating the learners' roles in the three areas- robot game, robot design, and innovation project that are highlighted in the literature (Hsu & Tsai, 2024). The findings from the observational study, alongside the relevant documentation, illuminated the challenges faced by the three participants in effectively incorporating technology to enhance learning experiences. The instructional plans developed for the Engineering and Robotics (ER) sessions demonstrated a tendency to present technological applications straightforwardly, often neglecting critical pedagogical strategies such as the progressive introduction of tools, the provision of clear instructions, hands-on demonstrations, and sufficient time for exploration. As noted elsewhere in other studies (Subramaniam et al., 2025; Yang, 2025), there was a lack of consideration for supporting technologies that could enrich the learning experience, such as artificial intelligence (AI), online research platforms, pertinent online videos, and beginner-friendly robotics simulators like VEXcode VR and Tinkercad Circuits. This oversight was particularly pronounced within the context of the innovation project.

The recommended pedagogical approach for engaging learners is rooted in the engineering design process, which encompasses stages including problem scoping, idea generation, design and construction, assessment of the design, and subsequent redesign and reconstruction. This method necessitates that learners possess a solid understanding of the content associated with their selected topic before engaging in the design and construction phase. While one trainer advocated for methodologies favoring self-directed learning, online research, and the utilization of AI to facilitate information retrieval on topics of interest, contrastingly, other trainers maintained a preference for delivering pre-prepared notes for learners to study overnight for subsequent presentation. This divergence in instructional approaches underscores the varying philosophies regarding the promotion of active versus passive learning within the ER context (Rodriguez, 2013).

Contextualization and Epistemic Engagement

The educators who participated in this study demonstrated a limited Pedagogical Content Knowledge (PCK) regarding the contextualization of curricular knowledge to align with local environments. This inadequacy was particularly evident in their approach to the thematic unit entitled 'Submerge.' Within this framework, students were tasked with designing robots and formulating missions, such as executing a rescue operation in deep ocean waters or developing innovative projects to address contemporary challenges faced by ocean scientists within marine ecosystems. These issues reside at the intersection of human concerns, global challenges, and the complexities inherent in deep-sea ecosystems. Notably, despite the country in which this study was conducted being landlocked, it possesses several water bodies, including lakes and artificial dams, which could have offered relevant immediate contexts for exploring themes related to submergence. The educators in this study neglected to reference these local contexts, failing to mention a nearby lake, a significant water body with a capacity of 330 million m^3 located merely three kilometers from the school. The discussion of concepts such as rising water temperatures and acidification, previously identified as problematic, could have been effectively initiated with a reference to the lake that students were familiar with. Tsarkos (2024) contends that this oversight highlights the importance of integrating local knowledge into the curriculum to enhance understanding and relevance in educational settings.

Further analysis of the observations revealed that educators facilitated opportunities for learners to construct knowledge, primarily through the inherent mechanisms of constructionist approaches embedded within the FIRST LEGO League manual, rather than through the direct efforts of the teachers themselves. Previous findings indicated a preference among teachers for learner engagement in memorization activities over project-based learning (PBL), suggesting a relatively low level of pedagogical epistemic knowledge (EIK) among these educators. This trend reflects a limited application of design-based engineering methodologies and an inability to differentiate between scientific inquiry and computational thinking (Alam & Mohanty, 2024; Wing, 2006). In an illustrative example, when ERT 1 was questioned about the significance of computational thinking within the context of ER, he was unable to articulate the connections between computational thinking, computer science, and programming. He notably struggled to explain how key elements such as decomposition, pattern recognition, abstraction, and algorithm design constitute essential components of computational thinking. This lack of linkage persisted despite ERT 1's participation in activities that encompassed these concepts during the instructional session. Consequently, the inability to align personal pedagogical actions with the demands of epistemic integration suggests pronounced deficiencies in achieving effective learning outcomes. ERT 2 further commented on this issue, indicating:

> *It is still a challenge for me to design the ER curriculum or session and deliberately incorporate knowledge areas such as inquiry and the CT you are talking about. Although, practically, that is what we do with the learners every day.*

The findings indicate that a substantial need exists for professional development among teachers to enhance their Epistemic Integration Knowledge (EIK). This development is essential to facilitate a transformative shift from traditional teaching roles to those of facilitators who are adept at engineering design principles, computational thinking, and the capacity to foster self-regulated learning among students. This underscores the importance of early-career educators grounding their development of integrated STEM pedagogical content knowledge (iSTEM-PCK) in the practical application of the engineering design process, project-based learning (PBL), and design-based learning (DBL), as well as cultivating proficiency in other interdisciplinary teaching methodologies (Yang et al., 2024; Yang, 2025).

In the context of CCK and EIK, the implementation of values development was approached with moderate effectiveness. Values development encompassed essential elements such as team building, peer coaching, mutual support, constructive feedback, and the promotion of enjoyment among participants. Throughout the educational process, educators actively engaged learners in the cultivation of these values. Despite earnest efforts to foster a supportive environment, certain values, particularly peer collaboration, demonstrated a tendency to thrive within learning frameworks such as Project-Based Learning (PBL) and collaborative learning paradigms, which the teachers had challenges implementing. Reflecting on the engagement of learners in values development, ERT 1 expressed the perspective that team building necessitated more than mere support from fellow team members. In the concluding section of the ER project report, he articulated the need for a more robust framework to facilitate genuine collaboration and teamwork among learners, intimating:

> *Team building is vital for sustaining the morale of the team. It goes beyond just support from team members to include support from the school as well. The school's support in the form of uniforms or T-shirts, travel and subsistence allowances, time provision, and other welfare go a long way in building strong ER teams.*

This observation was pivotal, as it pertained equally to both students and educators. It is essential that teachers receive support from the broader institutional context to enhance their effectiveness. Literature (Demetroulis et al., 2023; Ortiz & Smith, 2015) indicates that robust teams engaged in effective ER training necessitate a diverse mix of experts and novices, allowing for a synergistic exchange of knowledge and the development of expertise among team members.

Conclusions and Implications

In this study, PCK was viewed as the total sum of the teacher's behaviors and practices that yield the best learning results for individuals or groups of learners. These behaviors and practices are drawn from the teacher's pedagogical knowledge repertoire, pedagogical reasoning, subject matter knowledge, knowledge of learning theories, reflections on past experiences, knowledge of the learners' diverse learning preferences, content representation abilities, and his/her skills in organizing the learning environment. Putting these intricate practices and requirements in a single PCK act for STEM teaching is no easy fit (Ellebæk et al., 2024; Martins & Baptista, 2024; Mientus et al., 2022). A teacher may be competent in one or two of the dimensions and be lacking in another. For instance, in the context of iSTEM teaching, a teacher may possess the majority of dimensions and lack in the subject matter knowledge of the other STEM disciplines involved in the integration matrix or be limited in their knowledge of STEM integration approaches. The implication is a poorly developed or limited STEM-PCK. Given this background, this study posited the Composite STEM-PCK model.

The composite STEM-PCK was viewed as the specialized, integrative knowledge that STEM teachers develop to effectively design and facilitate learning experiences that blend content, pedagogy, and epistemologies across multiple STEM disciplines. It is not the sum of individual disciplinary PCKs, but a synthesized, emergent knowledge base suited for interdisciplinary problem-solving and design. Tapping from previous theories such as TPACK that adds technological fluency to content and pedagogy (Mishra & Koehler, 2006), and the Interdisciplinary Knowledge Integration that endeavors to understand how to connect concepts, methods, and epistemologies across domains (Boix Mansilla, 2006), the model proposes ICK, CPK, CCK, TIK, and EIK that are key integrative components every STEM teacher must strive for. Following this framework, the study's findings revealed that the ER trainers' application of composite STEM-PCK ranged low-moderate. On one hand, the educators who participated in this study demonstrated limitations regarding the contextualization of curricular knowledge to align with local environments, while on the other, applying cross-disciplinary pedagogical knowledge (CPK) and technological integration knowledge (TIK) moderately. These findings underscore the substantial need for professional development among teachers to enhance their composite STEM-PCK. It was envisaged that this development was essential to facilitate a transformative shift from traditional teaching roles to those of facilitators who are adept at engineering design principles, computational thinking, and the capacity to foster self-regulated learning among students.

Limitations of the Study and Directions for Future Research

The findings of the current study have to be conceptualized in the context of its limitations. The study was an exploratory case study that involved three teachers. The sample size, though considered adequate in qualitative research approaches, is too small to make generalizations of the findings to broader contexts. Despite this limitation, the study posited a Composite STEM-PCK model that explicitly captures the multifaceted nature of STEM teaching by integrating content, pedagogy, curriculum, technology, and epistemology. This broadens the traditional PCK (Pedagogical Content Knowledge) model and aligns better with real-world interdisciplinary teaching needs. The *Epistemic Integration Knowledge (EIK)* component could provide a potential tool to understand *how knowledge is constructed and validated* in different STEM domains—a crucial but underemphasized aspect of STEM teacher knowledge that supports critical thinking and inquiry-based learning. Thus, the model extends Shulman's classic PCK framework into a *composite***,** *multi-dimensional* form specifically suited for STEM, where knowledge must be both deep (disciplinary) and broad (interdisciplinary). Because the model has not undergone field testing, future research can empirically investigate how its components develop, interact, or influence student outcomes, making the model both *theoretically robust* and *methodologically actionable***.**

Statements and Declarations

Acknowledgments: The authors express their gratitude for the support and collaboration provided by the administration, teachers, and students at the participating University of Rwanda College of Education Laboratory School. The successful completion of this study was significantly enhanced by the crucial permissions granted by the Principal and the insightful contributions from the participating teachers and Educational Robotics team students.

Declaration of Interest Statement: The authors declare no conflict of interest

Ethics Statement: This research was conducted following ethical guidelines in Clause 9 of University of Rwanda College of Education Laboratory School Rules and Regulations Charter, which permits the use of photographs, recordings, and other media from school activities for academic purposes. Informed consent was obtained where appropriate, and all necessary measures were taken to ensure confidentiality, voluntary participation, and the ethical treatment of participants throughout the study.

References

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? *International Journal of Science Education*, *30*(10), 1405–1416.

Adeoye-Olatunde, O. A., & Olenik, N. L. (2021). Research and scholarly methods: Semi-structured interviews. *Journal of the American College of Clinical Pharmacy*, *4*(10), 1358-1367.

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of educational research*, *81*(2), 132-169.

Alam, A., & Mohanty, A. (2024). Integrated constructive robotics in education (ICRE) model: a paradigmatic framework for transformative learning in educational ecosystem. *Cogent Education*, *11*(1), 2324487.

Al Hamad, N. M., Adewusi, O. E., Unachukwu, C. C., Osawaru, B., & Chisom, O. N. (2024). A review on the innovative approaches to STEM education. *International Journal of Science and Research Archive*, *11*(1), 244-252.

Bengtsson, M. (2016). How to plan and perform a qualitative study using content analysis. *NursingPlus Open*, 2, 8-14. https://doi.org/10.1016/j.npls.2016.01.001

Bergen, A., & While, A. (2000). A case for case studies: exploring the use of case study design in community nursing research. *Journal of Advanced Nursing*, *31*(4), 926-934.

Burnard, P., & Colucci-Gray, L. (2021). Reframing STEAM by posthumanizing transdisciplinary education: Towards an understanding of how sciences and arts meet and matter for sustainable futures. *Convergence Education Review*, *7*(2), 1-29.

Cepni, S., Aydin, M., Ada Yildiz, K., Birisci, S., Ozkan, C., & Yalabuk, C. (2024). Examining the impact of modified P3 task taxonomy-enriched educational robotics PD program on teachers' STEM content knowledge. *International Journal of Science and Mathematics Education*, *22*(1), 81-110.

Council, N. R. (2011). *Successful K-12 STEM education: Identifying effective approaches in science, technology, engineering, and mathematics*. National Academies Press.

Crippen, K. J., & Archambault, L. (2012). Scaffolded inquiry-based instruction with technology: A signature pedagogy for STEM education. *Computers in the Schools, 29*(1-2), 157-173.

Demetroulis, E. A., Theodoropoulos, A., Wallace, M., Poulopoulos, V., & Antoniou, A. (2023). Collaboration Skills in Educational Robotics: A Methodological Approach—Results from Two Case Studies in Primary Schools. Education Sciences, 13(5), 468. https://doi.org/10.3390/educsci13050468

Ellebæk, J. J., Larsen, D. M., & Auning, C. (2024). Teachers' challenges in teaching integrated STEM: In the light of PCK as an analytical lens. *LUMAT: International Journal on Math, Science and Technology Education*, *12*(4), 13-13.

Hartelt, T., Martens, H., & Minkley, N. (2022). Teachers' ability to diagnose and deal with alternative student conceptions of evolution. *Science Education, 106* (3), 706–738. https://doi.org/10.1002/sce.21705

Hussain, S., Lindh, J., & Shukur, G. (2006). The efect of LEGO training on pupils' school performance in mathematics, problem solving ability and attitude: Swedish data. *Educational Technology & Society, 9*(3), 182–194.

Hsu, C. Y., & Tsai, M. J. (2024). Predicting robotics pedagogical content knowledge: The role of computational and design thinking dispositions via teaching beliefs. *Journal of Educational Computing Research*, *62*(5), 939-961.

Keiler, L. S. (2018). Teachers' roles and identities in student-centered classrooms. *International Journal of STEM education,* 5, 1-20.

Lowell, V. L., & Moore, R. L. (2020). Developing practical knowledge and skills of online instructional design students through authentic learning and real-world activities. *TechTrends*, *64*(4), 581-590.

Mansilla, V. B. (2006). Interdisciplinary Work at the Frontier: An empirical examination of expert. *Science*, *294*, 5547-1651.

Markauskaite, L., & Goodyear, P. (2016). *Epistemic Fluency and Professional Education: Innovation, Knowledgeable Action and Actionable Knowledge.* Springer.

Martins, I., & Baptista, M. (2024). Teacher professional development in integrated STEAM education: A study on its contribution to the development of the PCK of physics teachers. *Education Sciences*, *14*(2), 164. https://doi.org/10.3390/ educsci14020164

Mientus, L., Hume, A., Wulff, P., Meiners, A., & Borowski, A. (2022). Modelling STEM teachers' pedagogical content knowledge in the framework of the refined consensus model: A systematic literature review. *Education Sciences*, *12*(6), 385. https://doi.org/10.3390/educsci12060385

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers college record*, *108*(6), 1017-1054.

Moraiti, I., Fotoglou, A., & Drigas, A. (2022). Coding with block programming languages in educational robotics and mobiles, improve problem solving, creativity & critical thinking skills. *International Journal of Interactive Mobile Technologies, 16*(20), 59–78.

Nathan, M. J., Srisurichan, R., Walkington, C., Wolfgram, M., Williams, C., & Alibali, M. W. (2013). Building cohesion across representations: A mechanism for STEM integration. *Journal of Engineering Education*, *102*(1), 77-116.

Obeng-Odoom, F. (2019). Pedagogical pluralism in undergraduate urban economics education. *International Review of Economics Education*, *31*, 100158.

Ong, Q. K. L., & Annamalai, N. (2024). Technological pedagogical content knowledge for twenty-first century learning skills: The game changer for teachers of industrial revolution .0. *Education and information technologies*, *29*(2), 1939-1980.

Ortiz, A. M., Bos, B., & Smith, S. (2015). The power of educational robotics as an integrated STEM learning experience in teacher preparation programs. *Journal of College Science Teaching*, *44*(5), 42-47.

Padalkar, S., Ramchand, M., Shaikh, R., & Vijaysimha, I. (2022). *Science Education: Developing Pedagogical Content Knowledge*. Routledge. https://doi.org/10.4324/9781003047506

Ponticorvo, M., Rubinacci, F., Dell'Aquila, E., & Marocco, D. (2022). Coding and educational robotics with peers: The C0D1NC experience to foster inclusion. *Frontiers in Robotics and AI,* 9, 825536. https://doi.org/10.3389/frobt.2022.825536

Rodriguez, G. M. (2013) Power and agency in education: Exploring the pedagogical dimensions of funds of knowledge, *Review of Research in Education, 37*, 87- 120.

Schneider, R. M., & Plasman, K. (2011). Science teacher learning progressions: A review of science teachers' pedagogical content knowledge development. *Review of educational research*, *81*(4), 530-565.

Shulman, L. S. 1986. Those Who Understand: Knowledge Growth in Teaching. *Educational Researcher, 15*(2), 4–14. https://doi.org/10.3102/0013189X015002004 .

Subramaniam, R. C., Morphew, J. W., Rebello, C. M., & Rebello, N. S. (2025). Presenting STEM ways of a thinking framework for engineering design-based physics problems. *Physical Review Physics Education Research*, *21*(1), 010122.

Thyssen, C., Huwer, J., Irion, T., & Schaal, S. (2023). From TPACK to DPACK: The "Digitality-related pedagogical and content knowledge"-model in STEM-education. *Education sciences*, *13*(8), 769.

Tsarkos, A. (2024). Enhancing Teacher Readiness and Retention in STEM Education Through PCK Development. In D. L. Sargent & K. L. Murphy (Eds.), *Transforming Teacher Preparation Through Identity, Development, and Effective Technologies* (pp. 320-347). IGI Global.

Tyas, R. A., Wilujeng, I., & Rosana, D. (2025). An examination of preservice science teachers pedagogical content knowledge: Development and trends. *Multidisciplinary Reviews*, *8*(9), 2025279-2025279.

Wells, P. R., Goodnough, K., Azam, S., & Galway, G. (2023). Changes in high school distance education science teachers' pedagogical content knowledge (PCK) during remote lesson study. In R. Huang, N. Helgevold, J. Lang, & H. Jiang (Eds.), *Teacher Professional Learning through Lesson Study in Virtual and Hybrid Environments* (pp. 203–222). Routledge. https://doi.org/10.4324/9781003286172-15

Wing, J. M. (2006). Computational thinking. *Communications of the ACM, 49*(3). 33-35. https://doi.org/10.1145/1118178.1118215

Yang, W., Su, J., & Li, H. (2024). Demystifying early childhood computational thinking: An umbrella review to upgrade the field. *Future in Educational Research*, *2*(4), 458-477.

Yang, W. (2025). A three-phase professional development approach to improving robotics pedagogical knowledge and computational thinking attitude of early childhood teachers. *Computers & Education*, *231*, 105282.

Yin, R. K. (2003). *Case study research: Design and methods* (3rd ed.). Sage.

Yip, S. Y. (2025). Transition into teaching: examining the pedagogical content knowledge (PCK) development of pre-service STEM career-change teachers. *Journal of Education for Teaching*, 1-16. https://doi.org/10.1080/02607476.2025.2471901

Appendix. Analysis Rubric to Determine Levels of PCK Application under Each of the Five Components of the Composite STEM-PCK Model

Ordinal Categories	Definition	Indicators / Evidence in Interview	Examples of Quotes
PCK Greatly Applied	The participant demonstrates deep integration of pedagogical knowledge with subject content, adapting instruction to student understanding and context.	- Specific examples of instructional strategies aligned with student misconceptions or prior knowledge -Use of formative assessment to adapt teaching -Evidence of content-specific teaching strategies -Reflective practice on teaching decisions -Mention of student learning outcomes or engagement improvements	"I noticed many students struggled with this concept, so I used a model-based explanation and paired it with a real-life application..."
PCK Moderately Applied	The participant shows some integration of pedagogical and content knowledge, but with limited adaptation to student needs or context.	- Use of some content-specific methods, but not clearly linked to student understanding -General awareness of instructional strategies, but inconsistent application -Few examples of differentiation based on student needs	"I usually explain the topic using diagrams, though I haven't changed much from year to year."
PCK Not Applied	The participant uses generic teaching approaches with little or no integration of content-specific pedagogy or student-centered strategies.	- No mention of adapting instruction based on student understanding -Heavy reliance on the textbook or the lecture without explanation of the method -Lack of reflection on teaching effectiveness or student learning	"I just go through the textbook chapter by chapter and make sure I cover all the content."