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”What you bring matters”: A Comparative Case Study of Middle School Engineering Teachers' Pedagogical Content Knowledge (Fundamental)

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Abstract

Pre-college engineering teachers bring unique backgrounds to their teaching practice. Many engineering teachers follow a non-traditional route to teaching engineering, often coming to engineering from teaching other subjects or from careers in other fields. Among the many variations influencing engineering teaching practices is pedagogical content knowledge (PCK), defined as the "the knowledge of, reasoning behind, and enactment of the teaching of particular topics in a particular way with particular students for particular reasons for enhanced student outcomes [1]". This multiple case study explores the PCK of five middle school engineering teachers implementing the same middle school engineering curriculum, STEM-ID. The 18-week STEM-ID curriculum engages students in contextualized challenges that incorporate foundational mathematics and science practices and advanced manufacturing tools such as computer aided design (CAD) and 3D printing, while introducing engineering concepts like pneumatics, aeronautics, and robotics.

Drawing on observation and interview data collected over the course of two semester-long implementations of STEM-ID, the study addresses the research question: What variations in PCK are evident among engineering teachers with different professional backgrounds and levels of experience? Five teachers were purposively selected from a larger group of teachers implementing the curriculum because they represent a range of professional backgrounds: one veteran engineering teacher, one former Math teacher, one former Science teacher, one former English/Language Arts teacher, and one novice teacher with a background in the software industry. The study utilizes the Refined Consensus Model of PCK to investigate connections between teacher backgrounds, personal PCK (pPCK), the personalized professional knowledge held by teachers, and enacted PCK (ePCK), the knowledge teachers draw on to engage in pedagogical reasoning while planning, teaching, and reflecting on their practice. Observation, interview, and survey data were triangulated to develop narrative case summaries describing each teacher's PCK, which were then subjected to cross-case analysis to identify patterns and themes across teachers.

Findings describe how teachers' backgrounds translated into diverse forms of pPCK that informed the pedagogical moves and decisions teachers made as they implemented the curriculum (ePCK). Regardless of the previous subject taught (math, science, or ELA), teachers routinely drew upon their pPCK in other subjects as they facilitated the engineering design process. Teachers with previous experience teaching math or science tended to be more likely than others to foreground the integration of math or science within the curriculum. Comparison of ePCK observed as teachers implemented the curriculum revealed that, in spite of having a more fully developed pPCK in teaching engineering, the veteran engineering teacher did not exhibit more sophisticated ePCK than novice engineering teachers. In addition to contributing to the field's understanding of engineering teachers' PCK, these findings hold implications for the recruitment, retention, and professional development of engineering teachers.

Introduction

Shulman [2] described pedagogical content knowledge (PCK) as one of seven knowledge bases (i.e., content knowledge, general pedagogy, curricular knowledge, PCK, learners and their characteristics, educational context, and educational purpose*)* for teaching. Shulman [3] defines PCK as "the special amalgam of content and pedagogy that is uniquely the province of teachers, their special form of professional understanding". Thus, PCK involves teachers' understanding of both *the what* and *the why* of subject matter along with the circumstances that influence student mastery of subject matter. However, early PCK research did not adequately address the learning contexts or their linkages to student understanding and achievement [4]. Studying PCK is complex, as teachers, students, school- and district-level policies, among other contextual factors necessarily mitigate teaching and learning. Thus, for PCK to positively impact student learning, teacher *knowledge* must "manifest itself as action" [4]. Teachers require both a deep understanding of content *and* how to transfer this knowledge in accessible, practical, and meaningful ways. With increased calls for documenting best practices in content and pedagogy in STEM disciplines [5], [6], [7], it is essential to carefully examine PCK.

Although engineering has gained prominence in K-12 education [8][9], [10] research exploring the PCK of engineering teachers remains relatively scarce. As summarized below, studies have begun to investigate technological PCK for teaching the engineering design process (EDP) [11], [12] and relationships between science teaching practices and PCK for teaching integrated STEM [13]. However, more studies are needed to highlight systematic ways in which teachers utilize and develop PCK in the context of K-12 engineering education. As part of an NSF funded project conducting research on the implementation of the STEM-ID curriculum, we investigated the PCK of five middle school engineering teachers implementing semester-long curriculum in their 6th, 7th, and 8th grade classrooms. Drawing on the refined consensus model (RCM) of PCK, this comparative case study addresses the following research question: What variations in PCK are evident among middle school engineering teachers with different professional backgrounds and levels of experience?

Previous Research

Pre-college engineering teachers bring unique backgrounds to their teaching practice. Many engineering teachers follow a non-traditional route to teaching engineering, often coming to engineering from teaching other subjects or from careers in other fields. Compared to other STEM teachers, engineering teachers are less likely to have engineering-specific certifications or education. According to the National Teacher and Principal Survey, only 19% of K-12 engineering teachers majored or minored in engineering and 19% of engineering teachers do not hold a bachelor's degree, which may reflect the movement of skilled tradespersons from other fields into teaching[10]. Grier and Johnston [14] explored the identities of six STEM career changers who came to teaching from other STEM careers and found that career changers relied upon proficiencies developed in previous careers as they entered the teaching profession. The current study builds on this work by exploring the PCK of teachers who came to teach engineering from various backgrounds.

The research base on PCK in K-12 technology and engineering has begun to grow, with a number of studies drawing connections between engineering and technology teachers' previous experience and background and their engineering teaching experience. For example, Love and Wells [15] found that engineering and technology teachers' years of teaching experience was not as strongly correlated with science pedagogical practices as their formal and informal preparation experiences. These formal and informal experiences range from taking Physics as a high school student to completing an undergraduate robotics course to professional development. Such studies lend some insight into *how* teachers' PCK develops. Other recent studies aim to specify frameworks describing the particular forms of teacher knowledge and practices central to effective engineering teaching [16], [17]. For example, Demirici & Purzer's [16] engineering integration framework describes five knowledge bases guiding teachers' practices: orientation to teaching engineering, engineering integration, curriculum, students' understanding of engineering, and engineering teaching strategy. Ali & Maynard's [18] engineering design framework proposes using AI to allow students to present solutions by considering the impact of their designs. In their framework, Ali & Maynard [18] describe how each solution shows *how* and *why* they are appropriate. In this way, the framework operationalizes PCK as a *tool* for teaching rather than understanding PCK as a construct.

Engineering provides an authentic context for the application of science and mathematics [19]. Further, as science and mathematics are inherent in engineering, the pedagogy of mathematics and science teaching certainly applies in engineering classrooms. As such, the RCM, developed by researchers in mathematics and science education, is well suited for examining the teaching and learning of engineering curricula based on foundational mathematics and science concepts and skills. Further, teaching engineering demands attention to the collaborative nature of engineering design and the existence of multiple pathways to solutions [20]. Exploring how engineering teachers respond to and assess students' understandings and what prior knowledge and experience they draw from in formulating such responses, may contribute to greater understanding of engineering PCK as an educational construct.

Theoretical Framework: The Refined Consensus Model (RCM)

The RCM of PCK was iteratively developed by education researchers in science and, to a lesser extent, mathematics education to bring conceptual clarity to the study of PCK. Although the RCM has since been utilized primarily in science education, the significant overlap and application of science (and mathematics) in engineering, along with the general applicability of the definitions within the model suggest its likely utility for the study of engineering teachers' PCK as well. Indeed, in a recent review of PCK research, [12] tentatively concluded that "the majority of PCK models can be captured by the RCM".
The RCM is a five-layered, concentric, and interconnected model highlighting PCK. Carlson et al. [21] described this model as follows, beginning with ePCK at the center of the concentric model and moving outward:

1. Enacted PCK (*e*PCK)— the <u>unique subset of knowledge that a teacher draws on</u> to engage in pedagogical reasoning while planning, teaching, and reflecting on a lesson.

2. Personal PCK (*p*PCK)—the cumulative and dynamic personalized professional knowledge of an individual teacher that reflects the teacher's own teaching and learning experiences, as well as the contributions of others.
3. Collective PCK (*c*PCK)—specialized professional knowledge held by multiple educators in the field.
4. Learning Context—factors influencing teaching and learning, such as federal and school policies, community values, and student attributes.
5. Professional Knowledge Bases—various aspects of a teacher's broader professional knowledge bases, including science content knowledge, pedagogical knowledge, knowledge of students, curricular knowledge, and assessment knowledge.

Beyond the definitions above, a number of specific concepts related to ePCK and pPCK are of particular relevance for the current study. Regarding ePCK, the framework specifies that enactment applies not only to knowledge and reasoning invoked as teachers interact with students but also when teachers engage in planning or reflecting on instruction. Thus, to the extent that teachers reflect or articulate plans for future enactment during interviews, it is possible to document PCK with data gathered both through classroom observations and interviews. According to the model, ePCK is a subset of pPCK, which represents a "reservoir of knowledge and skills that the teacher can draw upon during the practice of teaching" [21]. As teachers' pPCK develops over time through formal education, teaching experiences, and professional sharing, pPCK is necessarily unique to each individual teacher. This uniqueness is one factor that motivated our use of a multiple case study approach to begin to understand variations in PCK among teachers with different backgrounds. Between each of the concentric circles of the model, arrows indicate a two-way knowledge exchange whereby "the knowledge and skills a teacher possesses from each realm are filtered and amplified in ways that shape a teachers' personal PCK" over time [21]. Although our research program is interested in developing understandings of these transformations between forms of PCK, for the current study, we focus on documenting enacted and personal PCK (ePCK and pPCK) rather than attempting to describe the interplay between teachers' pPCK and ePCK.

Methods

This multiple-case study [22] triangulated interview and classroom observation data to explore variations in PCK among engineering teachers of diverse educational and professional backgrounds. In describing the rationale for selecting a multiple-case study design, Yin [22] notes that multiple cases can be considered as one would consider multiple experiments, with cases carefully selected to either replicate similar results (literal replication) or to predict contrasting results for anticipatable reasons (theoretical replication). In the current study, the theoretical replication logic applies in that, based on the definitions and propositions put forward in the RCM model, we selected cases that, theoretically, would be expected to yield variations in the PCK data. Specifically, through careful analysis of five cases in which engineering teachers brought distinct educational and professional backgrounds to the task of curriculum implementation, we use the multiple-case study design to surface and document variations in enacted and personal PCK. The curriculum context, participants, data sources, and data analysis are described below.

Curriculum Context

The STEM-ID curriculum is comprised of three, semester-long 6th, 7th, and 8th grade engineering courses, each designed to develop specific, foundational STEM skills leading up to a final design challenge. Table 1 summarizes the major activities included in each grade-level course. The study was conducted over a one-year period spanning the 2023-24 school year.

The STEM-ID curriculum is a multi-year course sequence designed for 6^{th}, 7^{th}, and 8^{th} grade engineering classrooms. Each course is organized around a series of contextualized problem-based challenges designed to engage students in the engineering design process (EDP) while reinforcing foundational mathematics and science. In each course, students build skills through several types of challenges: Data Challenges, Systems Challenges, Visualization Challenges, and a culminating Design Challenge. See Table 1 for an overview of the challenges by grade level.

Table 1
STEM-ID Course Overview

Course	Description
6th Grade "Carnival Tycoon"	Students explore the engineering design process and entrepreneurial thinking in the context of a carnival. The course begins with students making a sales pitch for a new carnival food stand based on market research. Students then run experiments using a pneumatic catapult, and they must design a new carnival game board with appropriate odds of winning. Then, after skill development in engineering drawing, they re-design the catapult cradle to change the performance characteristics of their carnival game. Students incorporate math and science content, including data representation, probability, experimental procedures, profit calculations, drawing, and measurement.
7th Grade "Flight of Fancy"	Students pose as new airline companies and redesign airplanes to be more comfortable, profitable, and environmentally friendly. This is accomplished through a series of challenges, starting with a test flight of different Styrofoam gliders. Students examine interior layouts, learn 3D modeling in Iron CAD, and finally, re-design a plane using a balsa glider as a model. Students incorporate math and science content, including measurement, proper experimental procedure, data analysis, and profit calculations.
8th Grade "Robot Rescue"	The course is intended to further build student understanding of the engineering design process and entrepreneurship. The course begins with a short design challenge, requiring the students to design and 3D print a cell-phone holder. Students then conduct experiments using a bio-inspired walking robot. The course ends with an open-ended challenge to design a rescue robot capable of navigating variable terrain. During these challenges, students use robotics, 3D CAD modeling software, and 3D printing technologies. In addition, students incorporate math and science content, including modeling, data analysis, scientific procedure, force and motion concepts (e.g., velocity, speed, friction), and systems thinking.

Participants

Participants include five teachers from five different middle schools in a large metropolitan school district in the southeastern United States. The district, considered to have one of the most diverse student populations in the state, reports between 60 to 95 percent minority enrollment across schools. Case study teachers were purposively selected from a larger group of teachers implementing the curriculum because they represent a range of professional backgrounds: one veteran engineering teacher (Jim), one former math teacher (Sally), one former science teacher (Shannon), one former English/Language Arts teacher (Ellen), and one novice teacher with a background in the software industry (John). During the year in which data were collected, one teacher (Sally) was in her second year implementing the curriculum; all other teachers were implementing the curriculum for the first time. All teachers participated, together, in the program's summer professional learning institute, a 5-day series of experiential learning workshops in which teachers worked through each grade level course, gained technical expertise with equipment and materials used in the curriculum, and engaged in collaborative instructional planning to develop plans for implementation in their classrooms. Teachers also participated in several day-long professional learning workshops on particular topics (e.g. robotics, CAD) during the school year. Table 2 presents information on demographics and teaching background, including total years teaching experience, years teaching engineering, and years teaching STEM-ID*, as of the beginning of the 2023-24 school year. Cases are identified using pseudonyms.

Table 2
Case Study Participants

Teacher **Pseudonym**	Total Years Teaching	Years teaching engineering	Years teaching STEM-ID	Professional and Educational Background	Race Gender
Sally	15	1	1	Former Math teacher B.A. and MAT in Education	White Female
John	0	0	0	Industry Background: 20 years as Computer Science Engineer B.S. in Computer Science	White Male
Shannon	6	1	0	Former Science teacher B.S. in Communications, MAT in Middle Grades Math and Science	White Female
Ellen	8	0	0	Former Language Arts teacher BASc in Secondary Education and Teaching	Hispanic Female
Jim	21	21	0	Career engineering teacher B.S., M.A. in Social Sciences	White Male

Data Sources

The study triangulates observation and interview data collected for each case study teacher during the 2023-24 academic year. Table 3 below lists the number of observations and interviews conducted with each participating teacher. Note that the disproportionate number of observations conducted in Sally's classroom were due to her implementation of robotics activities at the end of the 8th grade curriculum, which other teachers did not get to. Because the project's curriculum development team made substantive changes to robotics materials for this iteration of implementation, the project decided to conduct additional observations in Sally's classroom to document implementation of the updated robotics activities.

Table 3
Observation and Interview Data Collected by Case

Teacher	Classroom Observation		Interviews	
	Extended	Short	Individual	Group Check-In
Ellen	14	3	2	2
Jim	16	4	2	5
John	20	5	2	5
Sally	51	3	2	3
Shannon	25	3	2	5

Classroom Observations

Researchers conducted observations in each teachers' classroom each semester of the 2023-24 school year. Classroom observations included both extended observations and short observation visits. For intensive observations, researchers observed full class sessions in each grade level over a two- to three-week period. A total of 126 class sessions were observed during these intensive observation visits. Short observation visits provided a snapshot of implementation and were also helpful for tracking implementation progress. For short observation visits, researchers observed one class period followed by a short consultation with teachers regarding implementation progress. A total of 18 short observation visits were conducted.

Observations were guided by a semi-structured protocol designed to gather data on key components included across the curriculum (e.g. engineering design process, math/science integration) while remaining sufficiently general to be used for all three grade level courses. The protocol included both checklist items and space devoted to both general field notes and field notes related to these key components. For example, in the section of the protocol aligned to the Engineering Design Process, observers indicate which of the six stages of the process students engaged in and then record accompanying written observations in the space provided. The protocol also includes space for observers to record field notes as evidence of pedagogical content knowledge, referred to as PCK episodes. For each PCK episode, observers were asked to identify the type of PCK (ePCK, pPCK, cPCK) as well as whether the PCK observed related to science, mathematics, engineering, and/or the STEM-ID curriculum. Note that although we anticipated the majority of observations to relate to ePCK, pPCK and cPCK were included in the protocol in order to document any instances in which teachers specifically reference the source or motivation behind their teaching moves or the ways in which their teaching was informed by their professional community. Observers were instructed to record PCK episodes in as much detail as possible so that they could be referenced during discussion of PCK in subsequent teacher interviews.

Teacher Interviews

Semi-structured interviews lasting 30-45 minutes were conducted with teachers at the end of each semester, following completion of the curriculum. In order to allow researchers to pose follow-up questions related to observations, interviews were conducted by the same researcher who had conducted observations in the teachers' classroom. Interviews were guided by a semi-structured protocol developed by project researchers. In addition to questions intended to document enactment and teachers' experience implementing STEM-ID, the protocol includes a stimulated response question designed to elicit reflections on a particular PCK episode captured in observation data. For this question, interviewers first describe the episode based on field notes and then confirm that the teacher recalls the episode. Then, the researcher uses a series of prompts to invite the teacher to reflect on the PCK episode:

- Tell me about your decision to _________.
- What previous experience do you think you were drawing on in that moment?
- Where did you learn about how to teach in that way?
- How has your experience with that group of students influence how you taught _____?

In addition to individual interviews, teachers participated in a series of six online group discussions ("check-ins") held monthly over the course of the school year. In these discussions, teachers were invited to share updates, questions, and collaboratively troubleshoot any challenges related to implementation. Thus, check-ins served both as a strategy for fostering the project's professional learning community (PLC) and a method for tracking teachers' implementation progress and learning about factors influencing implementation. Check-in discussions were conducted using Zoom video conferencing software and were video recorded.

Data Analysis

We utilized sequential qualitative analysis[23] to describe examples of engineering teachers' ePCK and pPCK. Analysis involved several iterative rounds of coding. In the first round of coding, researchers focused on identifying all instances of PCK within observation protocols and interview transcripts including all observation field notes related to PCK, responses to the stimulated response interview prompts, and teacher reflections on their enactment of the curriculum that provided evidence of PCK. The second round of coding aimed to classify PCK data as ePCK, pPCK, cPCK, based on the RCM model definitions. Although the definitions provided in the model were helpful in distinguishing the types of PCK from a theoretical perspective, applying them to code data was somewhat challenging. Because ePCK and pPCK are closely interrelated, there was occasionally some difficulty discerning whether data should be coded as ePCK versus pPCK. Through frequent discussions, coders eventually reached clarity in coding definitions for the types of PCK and criteria for coding each. In a final round of coding, we went back through the data to confirm coding for the types of PCK based on refined definitions and discussion between coders.

Findings

This multiple-case study utilizes diverse cases to describe and understand the PCK of engineering teachers with different backgrounds and how this PCK becomes evident during curriculum implementation. Below we present short case summaries synthesizing observation and interview data for each case followed by cross case analysis identifying patterns and themes that emerged across teachers. In order to foreground findings related to pPCK and ePCK, both case descriptions and cross-cases analyses focus primarily on instances of pPCK and ePCK emerging from observation and interview data rather than describing more general patterns and variation in curriculum implementation across teachers.

Sally: "When you can create a cross-curricular link, it helps students learn."

Observations in Sally's class indicated several episodes in which she clearly drew upon her pPCK as a former mathematics teacher to reinforce or extend the foundational mathematics included in the curriculum. Specifically, observers noted instances of incorporating additional data collection tools and activities as students tested prototypes along with examples of incorporating geometry concepts as students engaged with CAD. In one episode, as 8th grade students collected test results for their robot foot designs, she asks them to determine both the mean time, as directed in the curriculum, and adds an additional step to identify the median time in their testing data. In the same activity, she introduces the concept of an "outlier" and asks students to identify outliers in their data and to exclude them from analysis. In another example, Sally had developed a data table not included in the curriculum for students to record test results, noting to the observer that "if you don't show them what to record, they aren't sure how to set it up."

Asked to reflect on these examples in interviews, Sally cites her specific experience with the curriculum, her experience as math teacher, and her teaching experience, more generally: "I know from being a teacher and from experience and research when I was in school and doing classes, when you can create a cross-curricular link, it helps the students learn, and then it also makes it easier for me to teach to say, 'Hey, you guys have prior knowledge on this. Think about how you did it, and in this case, let apply it here'. So that's the main driving force of that."

Similarly, she expresses enthusiasm for the curriculum's integration of mathematics and science, noting:

> "I love it. I like to do it as much as possible. I wish I had a better background in physical science, like the physics aspect of it, especially for my eighth graders, but that's something I'm working on developing."

Interestingly, in this response Sally both highlights her propensity for integrating mathematics and science along with what she sees as her responsibility to deepen her physical science background. In describing how her engineering teaching is informed by her math background, she states, "I try and pull in how data helps us make predictions and that's why we want little variation. That's something they do in math class in seventh grade." Indeed, at several points in each interview Sally cites specific math concepts and standards and where they fall in the middle school math curriculum relative to where students apply such concepts in her engineering class. Thus, Sally's knowledge of mathematics curriculum, along with the need and ideal timing for certain concepts to be reinforced, serves as a clear example of her pPCK in mathematics influencing her engineering teaching practice as she implements the curriculum.

In another PCK episode, Sally refers to a video she showed students earlier in the semester in which prototypes were discussed using the example of designing prototypes of Disney rides. In this discussion, she tells students that "A prototype is a 3D model on a smaller scale of an actual design. Why do you think a 3D model on a smaller scale is important?" She goes on to describe a prototype as "a shrunken version of everything that it's supposed to be" then connects it to the 8th grade curriculum activities: "For us, the robot wheels are small, and the cellphone holders are small so we can print to size, but when we talk about things on a larger scale, like a car, or Disney rides, they prototype a scaled model (a smaller version of the actual thing) and eventually work up to more detail to their prototype before they build the actual ride." In an interview conducted shortly after this episode, Sally described her reasoning for framing the discussion about scaling and prototyping in this way:

> "What anything I see is really abstract for the kids, or I know of concrete examples that exist, then I try and pull it in. And so, I can sit here and talk about scale model all day long. And some of the kids experience with it, they get that a model car is often a scale model of an actual car, but a lot of them haven't had experience or they don't understand... they don't make the connection. And in class, we don't always have the opportunity to build and to do that. So that's why I try and make it more concrete by showing them a real-world example. And same thing with the robot legs to tie in. We're doing rescue robots. People actually do this for a job. They actually use these things...to kind of make it more relevant."

In describing where her impulse to make the abstract concrete, Sally cites her experience implementing the curriculum the previous year: "I know that last year, first semester, the first time I taught it, I could tell by some of the kids when I was explaining it, they didn't really understand it or they didn't make that connection. So just based on previous experience with presenting the curriculum, you find what areas the kids understand and what areas you have to support a little."

Shannon: "That's an engineer answer to an educator."

PCK data gathered for Shannon's case suggest three tendencies related to her PCK: a focus on student mastery, enacting principled curriculum adaptations, and building technical expertise for engineering teaching. Both observation and interview data illustrate numerous instances in which Shannon made pedagogical decisions based on her assessment of students' mastery of the engineering design process. For example, observations documented how Shannon made minor adjustments in an introductory EDP activity enacted in subsequent class periods. Asked about the changes she made between classes, she noted that she "explained the EDP sequencing game better" after noticing confusion among students the first time. Similarly, at the beginning of another class session, Shannon shared with students her observation that the steps of the EDP they tended to be confused about were those involving iteration stating:

> “I know that we know the process. We’ve done the process. We live the process, but we forget sometimes that the steps in the process have specific labels. I think the ones we struggle with are the ones that we have to go back and do again.”

She then led students in an activity in which they identified examples of iteration in the EDP and how they “showed up” in the projects their projects.

In interviews, Shannon repeatedly frames her reflections on curriculum implementation in terms of student mastery of either the EDP or the mathematics or science concepts embedded within the curriculum. For instance, in the following interview excerpt, Shannon reflects on the value of math/science integration by sharing how she facilitated her 8th grade students developing their understanding of the concept of volume as they completed the cell phone holder project:

> “I think the students understand it a little bit better because it’s tangible to them. When we did our phone holders, giving them a volume that they were allowed to use was, it broke their little brains for a while, but when they saw what that meant and that they could make the shape or make the size, whatever it was they wanted, they understood a little bit better...and they did well with it. It really helped them understand. Even some of my students that really struggle in math, they were like, ‘oh, that’s all I have to do’. Even though I’m like, ‘well, this is a lot of steps, but you just kind of break it down, like alright, what parts of your creation are a rectangle? What parts are a triangle? We’re going to find those numbers and add them together, and that is your shape’”.

Shannon’s description of this episode illustrates her tendency to constantly, perhaps almost instinctively, assess students’ developing understanding (“it broke their little brains”; “they understood a little bit better”) and gives some insight into how she draws on her pPCK, to build student understanding (“you just kind of break it down”).

The principled adaptations Shannon made as she implemented the curriculum also provided compelling examples of both pPCK and ePCK. One observer noted that Shannon supplemented the 6th grade engineering drawing activity with a Venn diagram illustrating the differences between isometric and orthographic drawings. Asked about the addition of this diagram, Shannon shared that she made it after noticing student confusion about the different types of drawing and that she observed less confusion after using the diagram. In an example of a more substantive adaptation, in lieu of the final design challenge, Shannon challenged her 6th grade students who finished developing 2D carnival gameboards to redesign their games as 3D games, with design elements raised from the gameboards. In describing this adaptation, Shannon notes that “making it a 3D game ‘kind of changes everything’ and gives students additional opportunities to apply what they learned in the previous challenge:

> They’re getting the ability to go through the process again. They’re getting the ability to apply what they’ve already learned and they're solving another problem and getting a chance to do that design step without completely just changing up everything to be different to support the raft activity.”

Finally, we noted connections to PCK in Shannon's response to technical challenges that arose during implementation. In one interview, Shannon reflects on the challenge of addressing technical issues with some of the equipment used in the curriculum (depleted batteries for the catapults used in the 6th grade challenges):

> "I remember asking about it and they're like, 'oh, you just need to go and buy a marine battery charger and do this and this and this'. And I'm like, 'alright, that's an engineer answer to an educator. I don't fully understand what you're asking me to do... But I know this is my first year teaching engineering, so it's something that sounds really simple to someone else."

This distinction between an "engineer answer" and her understanding as an educator new to engineering highlights technical expertise as a developing area of pPCK for Shannon. This potential gap in pPCK for the technical aspects of engineering teaching was also evident in her reflection on troubleshooting issues with robotics equipment: "I think that is probably the one hurdle that I felt like I couldn't get over with my background knowledge, amount of time I have to solve the problem, and current resources." Although she expressed some frustration with technical issues, Shannon shared that she expected to be able to clear this "robotics hurdle" by building her understanding of robotics (pPCK) through self-study and PD during the summer. Perhaps due to her self-awareness regarding limited pPCK in some technical aspects of teaching engineering, we observed that Shannon often positioned herself as a learner alongside students. She described how she had advanced students with experience in the VEX robotics program assembling and troubleshooting robots for the 8th grade challenge. Similarly, in describing her experience working with the catapults in the 6th grade challenges, Shannon describes how she has students rotate through stations, with one station focused on using instructional videos provided by the project to help her troubleshoot malfunctioning catapults:

> "If you're with me, we literally just watch those videos that y'all provided on troubleshooting the catapults. And I watch them with the kids and then I have them come sit with me and say, 'okay, what's the first thing that we need to check? What's the second thing we need to check?' And sometimes, I mean, they would troubleshoot a whole catapult, find three different things that were wrong with it, and then they fix it and now they know how to do that. So when theirs stops working, they're not like 'Ms. _______, Ms. ______, my catapult!' They sit there and think, 'okay, what are the first two problems, power and air, and how can I check that? The power's on? How can I check that? The air]s flowing.'"

Ellen: "As a kid, when we had meaningful discussions...it meant a lot more to me."

Observations in Ellen's classroom revealed a blend of ePCK and pPCK episodes, often informed by an emphasis on her students' and her own understanding of STEM-ID. She reflected, "If it's a lesson that I have more understanding…then it [will] go smoother. But if not, I try to add more support because I know my students, and sometimes what's in the lesson isn't supportive enough." In one episode, Ellen demonstrated her adaptability by realizing mid-lesson that she needed to change her plans and transformed the lesson into guided instruction on 3D drawing. She then separated a small group at her desk and provided more direct instruction to assist them in Isometric Drawings. Ellen expounded on this decision during her interview: “I think the small group kids took a ton away from the small group. I did notice a giant change in all of their understanding.”

Having taught eight years of language arts to a variety of students, from special education to gifted students, Ellen brought in diverse teaching experience. However, she switched to engineering as “she longed to see kids apply their learning in a real-life…real-world settings.” She acknowledged that though she loved the “chaotic mess,” the transition was not easy since it was unlike the “succinct” nature of the language arts classroom with “students all doing something at the same time.” She appreciates the STEM-ID curriculum because “it taught her how to effectively and very purposefully teach each step of the engineering design process and iteration,” thus seeking to develop her pPCK in engineering.

Ellen’s integration of math and science episodes emphasized understanding concepts through reflection and discussion. She “pushed” activities emphasizing data collection and analysis and “built in more opportunities for the kids to do that more regularly.” In seventh grade, students collected data on the flight paths of gliders but also “talked about the mean and range and what they noticed, how the procedures had an effect on the change from the first to the second round of flights.” She continued to share:

> We [also] had more discussions about that data. So it was good the kids were engaged in it. I don’t know if I would see the same kind of engagement if I were teaching just math or science. I don’t know. I’ve never been in that room before. But as a kid, I was not super crazy about math and science. I was a language arts and social studies [‘person’], and if I had been in a class where I saw it applied like this and we had meaningful discussions about it, it would’ve meant a lot more to me. I think it would’ve clicked for me better as a kid.

Ellen incorporated reflections throughout her ePCK episodes and interviews. During observations, she regularly reflected on her pedagogical decisions and why this was important for students. She also reflected on her lesson plans, especially when change was necessary for understanding. She shared:

> “My biggest failure is that I don’t know how to—and I got to think about this, really reflect on it—I don’t know how to get them engaged in the actual iteration portion of it because they did not want to go back and redo work, so to speak. In their mind, that’s what they see it as, and I need to make that more interesting. If they hate iteration and they refuse to do it, what’s the point of the engineering design process, right?”

Jim: “The chaos part is not what I’m comfortable with.”

Observations of curriculum implementation in Jim’s classroom yielded fewer PCK episodes than other teachers, perhaps due in part to a somewhat lower level of curriculum implementation overall. Specifically, Jim chose to focus on and extend parts of the curriculum that involved independent computer-based work while forgoing the curriculum’s more collaborative, hands-on activities. For instance, in the 6th grade, rather than having students design and test gameboards using the pneumatic catapults, Jim extended the first carnival stand activity to have students design and model food trucks.

In interviews, Jim explained that this approach was due to challenges with classroom management and his expectations for the types of activities students could "handle." In the following reflection shared in his Fall semester interview, Jim shares his concerns about how his classroom may be perceived if he implements more hands-on activities:

> "I am concerned about, what if they come in and it's chaos and it's messy? That's kind of the, 'I want it to be a good show in here.' I want it to be good and I want anybody from the district or whatever...but I'm also very fearful of, 'what if it does look like unorganized chaos?'"

Jim states that he is "trying to get used to this whole new setup," suggesting that the pedagogy required to implement the curriculum may be a deviation from how he taught engineering in the past. Similarly, referencing his previous teaching experience and how it may have informed his current efforts to keep students engaged, Jim notes, "You don't have to give up everything you've known in the past. You can try to get something that holds them and holds you together, too." This emphasis on "holding it together" and Jim's apprehension about the appearance of chaos was echoed in his second interview when he notes that, although he is hopeful that he is making some progress in adjusting instruction to facilitate collaborative group work better, "the chaos part is not what I'm comfortable with."

We recognized that what Jim characterized as "chaos" translated to administrative concerns about excellent classroom management. Consequently, he struggled to transform pPCK from past engineering teaching to ePCK, which may be helpful in the effective implementation of STEM-ID. Furthermore, it seems that Jim may view engineering design challenges meant for exploration and collaboration as contrary to the pPCK informed by his past engineering teaching experiences, which emphasized a more organized and controlled learning environment, often favored by his administration. It is not uncommon for such contextual factors, among others, to affect the implementation process, as highlighted in past studies **Error! Reference source not found.**.

With the exception of the major adaptations of curriculum described above, PCK episodes that were noted in observations conducted in Jim's classroom were relatively brief exchanges with students or minor adjustments to instruction. We observed, for instance, that Jim listed the interior elements of a plane's interior (classes, galleys, lavatories) on the board for students, likely due to his anticipation that students did not know this vocabulary. In one discussion with students who were attempting to use more advanced CAD software (Blender) instead of TinkerCAD, Jim responded to a students' inquiry about an instruction manual saying,"I've had students in the past who have looked up tutorials for Blender."

One tendency potentially indicative of pPCK noted over several observations was Jim's strategy of providing students with a variety of tasks to choose from at the beginning of each class period. During a brief discussion following one of these episodes, Jim notes that he believes giving students choice promoted student engagement. However, when asked to reflect on this PCK episode in an interview, Jim did not elaborate on the utility of this strategy but rather shared his challenges regarding school-level expectations for evaluating student work. Taken together, these self-identified challenges of meeting expectations regarding assessment and classroom management seemed to have limited Jim's capacity to draw on relevant pPCK he may have developed as a veteran engineering teacher.

John: "It is surprisingly how similar the classroom and my director position kind of go hand in hand."

PCK data from John's classroom observations and interviews revealed his collaborative approach to teaching. Describing his teaching style as "very hands-on," John's pedagogy emphasized student engagement, as he saw engaging with "other people and being able to communicate properly…pivotal to success in business no matter what you decided to do." Moreover, as a first-year middle school teacher, he actively incorporated teaching and training tools from his twenty years of experience as an industry software engineer and manager to help students understand and apply the engineering design process within STEM-ID projects. In one observation episode, students are seen actively using Excel spreadsheets to assist them in collecting and analyzing data for board games. During John's interview, he expounded on the importance of this activity:

> So, I was a software engineer with a focus on data analytics, C-sharp development… SQL, as well as a data visualization specialist. So, as you've probably heard, there's a ton of data. I made sure that the students had at least experience with engaging with Excel formulas. I made sure that they had to load data into an Excel spreadsheet as opposed to just a list in Word. I built the structures of the catapult project in a way that it creates an XY coordinate plane that will show you that when you plug in the X and Y values of where the ball lands for each catapult shot, it adds a number to a separate tab that will show you exactly where on the game board each one of them lands so that you can physically, visually see where they landed. Then I made the students take that partially built data visualization and turn it into their catapult landing project solution, and that allowed the sixth graders to see where their balls were going to land, [and] easily convert the percentages because I had one tab that showed you where they land and count, and another tab that showed you where they land and a percent of the total so that they could physically see exactly how each one of the steps works. And that's how I use the data in my sixth-grade class.

Additionally, John's PCK episodes emphasized the importance of making connections between what students "should have" learned in science and mathematics and what they were learning in STEM-ID. In one lesson, he paired the engineering design process with the scientific method, hoping that students would realize the analogous relationship and see that the EDP was not *that* new. However, while some students had a "big aha moment," this was not the case for everyone. He described later in his interview:

> I was constantly trying to embed [math] in there…and so we've got the starting a business… and each of them talks about the math behind what you would need to start up a different type of business. We also incorporated [math] in the landing areas, the math for the statistics of where things land based on percentages. We had to talk about

> converting percentages to decimals, which I didn't realize I [needed] to do because I thought they understood that already. That was a mistake on my part. So, I try to embed math quite a bit in [assignments].

His own learning experiences informed John's pPCK. He incorporated the EDP into each lesson by highlighting the current phase and pointing this out on various posters in his classroom and during the introduction of each lesson. However, he noted that "unless you experience the engineering design process over and over and over again through project after project" students will not just automatically "get it." He cites his learning experiences as motivation behind his approach: "I was not a straight-A student. I was a BC student [who] worked really hard…and put in the extra effort…. [But] I…have to break things down to basic simple steps, or it just doesn't work for me." Constructive feedback is also embedded in John's PCK episodes. He described how he loves "breaking their stuff" to show students that a prototype needs "tweaking" to help support the iteration phase of the EDP. However, he knows that "some [students] don't really like having their problems shown, and certain ones really like to get the input," thus mirroring his experience as a manager:

> I look at it the same way as some of my employees when I used to work as the director. Some of them would like getting feedback and some of them didn't like getting feedback. It is surprisingly how similar the classroom and my director position kind of go hand in hand.

John also prioritized engaging with his fellow participants and sharing resources and approaches to learning content. He describes this as valuable to his experience as a teacher, as it can be lonely being the only engineering teacher at the school. He shared during his interview:

> Ultimately, you need to put a little bit more time and effort into making relationships between the STEM-ID participants. And the reason I say that is because the real value that I got out of this, above and beyond having something to build on, was the relationships with the other team members.

Cross-Case Analysis

Teachers' backgrounds translated into diverse forms of pPCK that informed the pedagogical moves and decisions teachers made as they implemented the curriculum (ePCK). As evidenced in the case summaries above, regardless of the previous subject taught (math, science, or ELA), teachers routinely drew upon their pPCK in other subjects as they implemented the curriculum. Cross-case analysis surfaced findings related to two other areas: PCK and Math/Science Integration and PCK and Engineering Teaching Experience.

PCK and Math/Science Integration

Teachers with previous experience teaching math or science tended to be more likely than others to foreground the integration of math or science within the curriculum. Although we did observe teachers supplementing the curriculum by bringing in relevant concepts they had taught as math or science teachers, the ways in which teachers drew on their math or science backgrounds did not always represent a straightforward importation of content knowledge or discipline-specific teaching strategies. For example, both Sally and Shannon drew on their curricular knowledge and understandings of typical learning progressions to integrate concepts when students would be most receptive for particular concepts or when students generally encountered certain standards as they progressed through middle school. Thus, these teachers did not integrate math and science concepts and skills simply because they had previous experience teaching them, but rather they drew on their pPCK in math and science to engage in pedagogical reasoning about when and how integration of concepts would be most effective.

PCK and Engineering Teaching Experience

Comparison of observed teachers of varying experience levels revealed that years of experience teaching engineering did not necessarily mean more sophisticated ePCK than novice engineering teachers. As a veteran engineering teacher, Jim brought more than twenty years of experience teaching engineering, and assumably more pPCK in engineering teaching than our other teachers who were in either their first or second year as engineering teachers. However, this experience did not necessarily translate into a clear advantage in ePCK. Indeed, although there were a few instances of ePCK observed, observation and interview data showed that Jim's utilization of any pPCK amassed over his years teaching engineering was eclipsed by his concerns about classroom management and assessment. In contrast, our other cases illustrate that certain elements of pPCK developed as core disciplinary teachers that are not specific to engineering, nonetheless, can facilitate effective engineering teaching. Teachers who had recently taught mathematics, science, or ELA (Sally, Shannon, Ellen), in which they were expected to cover all standards and prepare students for standardized tests, drew on their pPCK to focus on student mastery and tended to approach curriculum implementation overall with more seriousness than teachers who had not previously taught core subjects. As we have reported in other research on factors facilitating curriculum implementation [24], these teachers also demonstrated particularly strong time management and organizational strategies.

Interestingly, in the case of John, we saw evidence that PCK can come from unexpected sources, such as drawing on experience training and managing adults in an industry setting. Although he had not taught engineering at the middle school level, we noted PCK episodes in which John seemed to be drawing on his reservoir of knowledge gleaned from years of leading adults on data analytics and visualization projects. In John's case, he capitalized on the "exceptional similarities" between the engineering and project management design processes. Thoughts of real-world experiences often preceded his planning, enactment, and reflection of lessons and student engagement. As such, this *industry* discipline tended to guide not only his ePCK and pPCK episodes but also classroom management, student engagement, and classroom logistics.

Finally, we found that teachers recognized and, to varying degrees, seek to address limitations and potential gaps in their pPCK that may limit their enactment of curriculum. Sally and Shannon explicitly acknowledged their need to deepen their expertise in physical science and robotics, respectively. Similarly, in reflecting on the mismatch between his current, more traditional mode of teaching engineering and the collaborative, project-based approach required for the curriculum, Jim implies a need to expand his pPCK for engineering teaching. Due to her teaching background in ELA and her struggles in mathematics as a student, Ellen felt it was important to integrate math and science in "physical, literal, and applicable" ways, often checking for understanding in real time. Still, she acknowledged the need to become more effective in incorporating these strategies to enact the curriculum and manage classroom behavior fully. Furthermore, as in John's case, the curriculum was necessary for learning how to structure content, which was necessary to help him balance his need to manage class time wisely.

Discussion

Overall, this study lends support for the use of the RCM for developing understandings of engineering teacher PCK. Clearly, the same conceptualizations of PCK that have guided research in science and mathematics education are useful for understanding the PCK of engineering teachers. Within the model, ePCK is considered an interrelated subset of pPCK, and indeed, we did find that instances of ePCK and pPCK in our data were somewhat difficult to distinguish. However, determining whether a PCK episode represents the act of drawing on a reservoir of knowledge during the act of planning, teaching, or reflecting on instruction (ePCK) versus a reflection of the teachers individualized knowledge itself (pPCK) is less important than illustrating how both ePCK and pPCK are at work during engineering teachers' enactment of curriculum. Although this study aimed primarily to describe and provide examples of ePCK and pPCK, our findings began to illustrate the interplay between the two. Developing deeper understandings of this interplay between ePCK and pPCK and how it manifests in the context of engineering education represents a key future direction for our research program.

In addition to contributing to the field's understanding of engineering teachers' PCK, these findings hold implications for the recruitment, retention, and professional development of engineering teachers. Additional case studies of PCK in a broader range of experienced engineering teachers may highlight additional engineering-specific forms of pPCK and ePCK, such as pPCK related to how best to facilitate the engineering design process. At the same time, our case study findings suggest that all PCK, whether developed in engineering education settings, other disciplines, or even industry, matters. Indeed, the pPCK that teachers from core disciplinary subjects brought to their work as engineering teachers proved particularly beneficial for both efficient curriculum implementation and building student mastery. While there remains an imperative to provide quality pre-service experiences for teachers intending to teach engineering, our findings also point to a need for professional learning experiences that facilitate utilization of pPCK developed in other disciplines or settings for teachers transitioning to engineering. Additionally, while teachers from other subjects are often asked to teach engineering out of necessity due to the shortage of engineering teachers, our findings support thinking broadly about recruitment of engineering teachers and not necessarily prioritizing recruitment of teachers with extensive engineering teaching experience.

While this study lends new insights into the PCK of engineering teachers, it is not without limitations. As other researchers have noted, PCK is complex and documenting and eliciting the various forms of PCK can be challenging [21]. PCK is both ever-present and difficult to capture in observations and interviews. The study's reliance on observation field notes to inform stimulated-response questions is a clear limitation that may have resulted in overlooking PCK episodes that may have been captured using video data. Similarly, within our project, we found that observers with prior teaching experience tended to be somewhat better equipped to recognize PCK episodes. Along with the somewhat uneven distribution of observations data across teachers, these limitations mean that the study's data likely does not represent a comprehensive account of case study teachers' PCK.

The findings of this study underscore the pivotal role of the RCM in investigating the evolution of PCK in middle school engineering. By capturing the intricacies of teachers' pPCK and ePCK, the study highlights how teaching and learning can be transformed through targeted actions and teachers' prior experience. These actions shape pedagogy and serve as a rich source of learning for teachers, further adding to the pPCK repertoire. Moreover, by accentuating the nature of PCK variations, the results provide a roadmap for teachers to monitor their PCK growth in the context of teaching engineering, thereby illuminating a complex and crucial aspect of teaching and learning. As such, teachers could recognize, and students may benefit from what teachers bring to the engineering classroom teaching experience.

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