"Let the Designing Begin!": Teacher Tendencies Supporting Efficient Facilitation of the Engineering Design Process

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Abstract— **This research full paper utilizes qualitative methods to explore middle school engineering teachers' facilitation of the engineering design process as they implement STEM-integrated curricula. Engineering teachers face the challenge of guiding students through a multi-phase, iterative process to design, prototype, and test solutions to engineering problems. In our research exploring middle school teachers' implementation of the semester-long STEM-ID curricula, we have found considerable variation in the degree to which teachers successfully work with students to navigate the engineering design process (EDP). Some teachers have been able to guide students through the EDP to complete STEM-ID challenges efficiently, whereas other teachers have struggled to do so. To better understand the problem of practice evidenced by such variations in the efficiency of EDP facilitation, this qualitative study synthesizes observation and interview data to identify tendencies characterizing efficient facilitation of the EDP among teachers implementing the STEM-ID curricula. In the current study, which focused on curricula implementation by six engineering teachers, four teachers demonstrated efficient facilitation of EDP, successfully guiding students through the vast majority of the curricula's design challenges, while two teachers struggled to do so. Our qualitative data suggest three major tendencies that may account for variations in the efficiency with which teachers guided students through the various stages of the EDP: 1) adept management of student groups working at multiple stages of EDP, 2)explicit discussion of EDP progress and documentation in engineering design process logs, and 3) engaging students in discussions about the purpose of engineering and the engineering design process, including beyond the design challenges they complete as part of the STEM-ID curricula. By identifying tendencies we observed among teachers who efficiently implemented the EDP, we hope to advance the field's understanding of strategies that support student engagement in the EDP while also informing future engineering curricula and professional development projects.**

Keywords—engineering design process, K-12 engineering, middle school engineering, curriculum implementation, STEM integration

I. INTRODUCTION

Researchers have begun to explore how teachers manage the unique demands of teaching engineering, such as noticing and responding to students' novel, unanticipated design solutions [1], integration with other disciplines [2],[3],[4], and fostering specific skills and engineering practices [5],[6]. Extant research has provided critical insight into effective approaches to engineering instruction in a variety of contexts [7]; however, additional research is needed to gain a holistic understanding of EDP facilitation, examining issues such as how, within tight time constraints, teachers can best support students' navigation of the EDP. As part of an NSF-funded DRK-12 project conducting research on the implementation of the STEM Innovation and Design (STEM-ID) curricula, we investigated the facilitation of the EDP by six middle school teachers implementing semester-long curricula in their 6th, 7th, and 8th-grade classrooms. In light of differences in the degree to which teachers completed the curricula's design challenges, we were particularly interested in understanding variations in the efficiency with which teachers facilitated the EDP. That is, we sought to identify tendencies that distinguished teachers who capably led students through the STEM-ID design challenges in the time available from teachers who struggled to complete the design challenges. To this end, the study addresses the following research question: What tendencies characterized efficient facilitation of the EDP among teachers implementing the STEM-ID curricula?

II. Background

The implementation of the engineering design process (EDP) has gained widespread traction in K-12 education. Educators have embraced the EDP as an essential tool for cultivating engineering thinking, enabling effective decision-making, and averting oversights when addressing engineering challenges [8]. Since engineering design problems are often "ill-structured" with the potential for multiple satisfactory solutions, the EDP plays a pivotal role in exploring various problems and gathering information [9]. The EDP is widely integrated into formal STEM and science courses in K-12 education, with specific emphasis on engineering design practices varying based on teachers' backgrounds and experiences. For instance, research indicates that students and teachers across different age levels prioritize different stages of the design process due to their background knowledge [10], [11]. Thus, a superficial comprehension of the EDP may lead teachers to facilitate the EDP as a linear process lacking any explanation of purpose and rationality behind each stage [10]. In such scenarios, students may resort to a recipe-like methodology rather than embracing the EDP as an iterative process for resolving problems, with the aim of attaining efficient and suitable design solutions [10]. Given the challenges inherent in facilitating the EDP, along with the many contextual factors that may influence how engineering curricula are implemented [12], much can be learned by examining the tendencies of teachers who manage to guide students through the EDP efficiently.

III. Frameworks

This study is part of a larger implementation research agenda utilizing Century and colleagues' framework for examining innovation implementation, defined as "the extent to which innovation components are in use at a particular moment in time" [13]. As implied by this definition, the innovation implementation framework conceptualizes curricular innovations like STEM-ID as complex and comprised of essential parts or components. The framework defines two types of components: structural and interactional. Structural components are "organizational, design, and support elements that are the building blocks of the Innovation" and can be further divided into procedural components (organizing steps, design elements of the innovation itself) and educative components (support elements that communicate what users need to know). Interactional components include the "behaviors, interactions, and practices of users during enactment", generally organized according to user groups (e.g., teachers and students). Within the category of interactional components, pedagogical components focus on actions expected of teachers during implementation, and learner engagement components focus on student engagement while participating in the innovation. Teacher facilitation of the EDP and student engagement in the EDP were identified by the project team as critical interactional components, along with components related to the integration of mathematics and science, utilization of advanced manufacturing technology, and engagement in collaborative group work. Thus, data collection and analysis focused on characterizing to what extent and in what ways each of the critical components were evident as teachers and students interacted with the STEM-ID curricula.

Although models conceptualizing the EDP vary somewhat in the specific terminology used and the sequence of activities, many describe an iterative process for the development of design solutions. The EDP (Figure 1) served as an overall conceptual framework guiding curricula development and implementation. Specifically, STEM-ID was designed to employ the EDP within a problem-based learning context, combined with an emphasis on integrating science and mathematics practices. As such, teachers used this particular EDP model as they facilitated students' work with the curricula. Additionally, this EDP model informed the development of protocols and coding schemes used for the analysis of observation and interview data.

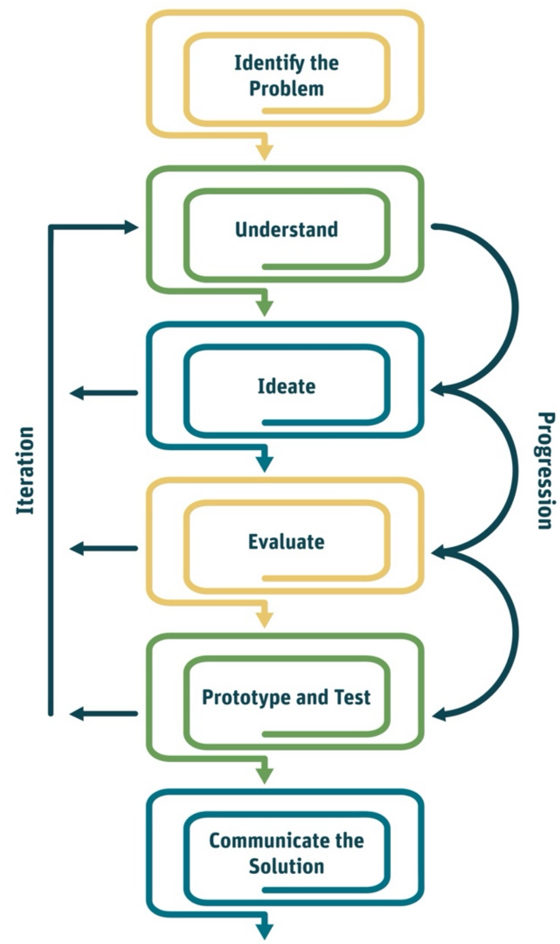

Fig. 1. Engineering Design Process

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IV. Methods

In addition to our application of the Innovation Implementation Framework, this basic qualitative study [14] is grounded in the tenets of design-based implementation research (DBIR) [15] and the tradition of "practice-embedded research" [16]. As such, the study is situated at the nexus of research and practice and aims both to contribute to engineering education scholarship and to address problems of practice in engineering education. The curriculum context, data sources, and data analysis are described below.

A. Curriculum Context

The STEM-ID curricula comprises three semester-long 6th, 7th, and 8th-grade engineering courses, each designed to apply foundational STEM knowledge and skills through a series of challenges leading up to a final design challenge. Table 2 summarizes the major activities included in each course. Based on promising results following a 4-year development and implementation period, our research team launched an NSF-funded DRK-12 project to scale STEM-ID to reach a broader population of engineering teachers and students. To this end, during the 2022-23 school year, STEM-ID was implemented by a cohort of six teachers in five schools within a large metropolitan district, with plans to add additional cohorts in subsequent years. Table 2 provides information about teacher participants' demographics and background.

TABLE 1. STEM-ID Curricula 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 sustainable. 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 LEGO® 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.

TABLE 2. Teacher Participant Background

Teacher[a]	Total years teaching	Years teaching engineering	Years teaching STEM-ID	Professional/ Educational Background	Demographics
Sally	15	0	0	Former Math teacher B.A. and MAT in Education	White Female
Neil [b]	29	8	4	Former Science teacher B.A. and MAT in Education	White Male
Kathryn [b]	5	0	4	Computer Science Teacher B.A. in Education	White Female
Stephanie	18	1	1	Former Math teacher B.A. in Mathematics, MAT in Education	Black Female
Jeanette	28	2	2	Former Science teacher B.A. in Biology, MAT in Education	Black Female
Pete	21	3	2	Former Science teacher B.A., MAT, and PhD in Education	White Male

Note: [a]teacher names are pseudonyms to protect confidentiality. [b] These two teachers co-teach the curricula in the same school.

B. Data Sources

The study synthesizes observation and interview data to describe teacher experiences facilitating the EDP. Each of these data sources is described below.

1) Classroom Observations

A team of four researchers observed the implementation of each grade level curriculum over an approximately two-week period in four teachers' classrooms (Sally, Neil, Stephanie, Jeanette). Researchers gathered data from a total of 80 class sessions. In order to track implementation more closely, additional short weekly observation visits (n=23) were conducted during the Spring 2023 semester. Due to scheduling conflicts and one teacher resigning from the project after the first semester, we were not able to conduct observations at all five school sites, and observations were somewhat unevenly distributed. In spite of this limitation in the observation data, the overall breadth of the observation dataset, when analyzed alongside interview data, provides considerable insight into the facilitation of the EDP. Observations were guided by a semi-structured protocol that included both checklist items and space devoted both to general field notes and field notes related to each critical component. In the section of the protocol aligned to the Engineering Design Process, observers complete a checklist item to indicate which stage of the process students engaged in and then record accompanying field notes in the space provided.

2) Teacher Interviews

Semi-structured interviews were conducted with each teacher at the end of each semester. In addition to questions intended to document implementation and elicit reflections on teachers' experience with the curricula, the protocol includes questions and follow-up prompts aligned to each critical component, including facilitation of the EDP. An excerpt of the interview protocol is provided in Table 3. Interviews lasted 45-60 minutes, with approximately 15-20 minutes of each interview focusing specifically on EDP facilitation. All teacher interview sessions were audio-recorded and transcribed for analysis. In addition to individual interviews, teachers participated in seven online group discussions over the 2022-23 school year. In these discussions, teachers were invited to share updates and questions and collaboratively troubleshoot challenges related to curricula implementation and facilitation of the EDP. Check-in discussions were conducted and recorded using Zoom video conferencing software.

TABLE 3. EXCERPT OF INTERVIEW PROTOCOL

Topic/Critical Component	Interview Question/Prompt
Self-efficacy	Overall, how confident do you feel about teaching the STEM-ID curricula? What aspects have been most challenging for you as a teacher? Can you share an example of a time you felt particularly successful? Can you share an example of a time you have struggled?
Curricula Implementation	Were you able to implement STEM-ID as you had hoped this semester? If not – what factors influenced your ability to implement STEM-ID? Were there parts of the curricula you didn't get to implement this year? Tell me about how you decided not to do ______.
EDP Facilitation	Let's discuss how your students engaged in the Engineering Design Process this semester. If you think about your overall experience teaching STEM-ID, how well do you believe your students understand the overall Engineering Design Process? Can you share an example of a time when students were particularly engaged while working through the EDP? Are there any misconceptions or areas of confusion that you've noticed regarding student understanding of the EDP? Are there particular stages of the EDP that are more challenging for your students than others? Now let's turn to your perspective on teaching the EDP. What strategies have you used as you've facilitated the EDP in your classroom? How frequently do you explicitly refer to the EDP as you teach STEM-ID? What stages of the EDP have been most challenging to facilitate? What advice would you give a teacher who is engaging students in the EDP for the first time? How do you support iteration as your students engage in the engineering design process? Describe any factors that have limited iteration as your students have engaged in the engineering design process.

C. Data Analysis

Interview and observation data were analyzed using a process of sequential qualitative analysis recommended by Miles, Huberman, and Saldaña [17]. A first round of coding focused on identifying instances within interview and observation data that illustrated the facilitation of the EDP. In a second round of coding, data were coded according to emergent themes characterizing tendencies related to EDP facilitation. In a final iteration of coding, data were combined across similar themes reflective of a core set of tendencies related to EDP facilitation. For example, data coded as reflective of time management, facilitating group work, and differentiation during EDP facilitation were ultimately brought together under one code to capture the tendency of managing students working at various stages of the EDP. All interview and observation data were coded using the NVIVO software program. Coded interview and observation data were then synthesized to create a series of conceptually clustered matrices describing implementation and findings. Specifically, these matrices included data illustrative of the various tendencies identified in the final round of coding arranged by teachers grouped by whether they had demonstrated efficient facilitation of the EDP. These matrices were then utilized to draft narrative summaries describing EDP facilitation.

V. RESULTS

Our qualitative analysis suggests several tendencies that may account for variations in the efficiency with which teachers guided students through the various stages of the EDP. Four teachers demonstrated efficient facilitation of EDP, successfully guiding students through the vast majority of the curricula's design challenges, while two teachers struggled to do so. Our analysis suggests that teachers who work most efficiently through the EDP with their students tend to do three things: 1) Adeptly manage student groups working at multiple stages of EDP versus having students work engage in "lock-step" fashion, 2) Explicitly discuss EDP progress and documentation in engineering design process logs, and 3) engage students in discussions about the purpose of engineering and the engineering design process, including beyond the design challenges they complete as part of the STEM-ID curricula.

The first tendency, the adept management of students working at multiple stages of the EDP, was evident in classroom observations where, within a single class period, individual students or groups meaningfully engaged in two or more stages of the EDP. In these teachers' classrooms, it was not uncommon to observe students in a single class period conducting research related to the design problem, brainstorming design solutions, using CAD to design prototypes, testing prototypes, and working on presentations to communicate their design solutions. Indeed, over 75% of observations where the EDP was observed in our efficient teachers' classrooms documented students working at multiple EDP stages. In contrast, in classrooms where progress was more limited, the teacher tended to guide students in a lockstep fashion, with over 90% of observations indicating that all or nearly all students completed the same activity within the same stage of the engineering design process before moving on as a class. In these class sessions, expectations for student progress tended to be modest. For example, in an observation of one teacher's 8th-grade classes, a 45-minute class period was devoted to photographing and uploading photos of the three potential designs they had sketched in the previous class period, a process that took most students about fifteen minutes to complete after which students engaged in off-task behavior or work for other classes.

It is not surprising that interview data from efficient facilitators of the EDP suggest teachers' organizational and time management skills as key teacher characteristics enabling implementation of the EDP. Each of the four teachers who demonstrated efficient facilitation cited the importance of adequately preparing to implement each of the curricula's challenges as critical for smooth facilitation of the EDP. Neil described how "having everything for the entire challenge ready to go" enabled him to "let kids go, let them work seamlessly through the process without waiting on me to get stuff ready". Sally describes her approach to managing student groups, describing how she drew on her previous experience as a math teacher to "set up a structure to the class" that allows her to monitor student progress but is flexible enough for groups to "work through the process, whatever stage they are in, on their own":

> *Once I got, uh, the hang of it, kind of set up a structure to the class where each day we do a morning check-in, then they work and I facilitate what they're working on. And then there are periodic, more in-depth check-ins...how I used to, with math class, you kind of have to have it more, it's very structured, whereas this is a little more flexible so kids can work through the process, whatever stage they are in, on their own. So, I was able to tie in some of that structure to at least create a routine so the kids knew what the expectation was.*

In a subsequent interview, Sally describes how strong time management has enabled differentiation such that she is able to support groups who may need extra help while providing extension activities for groups who finish more quickly, with the goal of all students have the opportunity to iterate on their designs:

> *Time management has been the biggest thing, and planning to have time to iterate has been helpful...because what happens is I get groups that finish, and they're done, and their thing works, especially with the sixth graders in the Catapult. And then I have groups that are still struggling and need help, and they do work on their presentations, but some groups get so far ahead it's finding some extension for them to do so that my other groups can have that time to iterate. So, it's just planning and making sure there's time and then differentiating so that the kids that need more time to iterate have that opportunity.*

Our most efficient facilitators of the EDP all reported that they explicitly and regularly discuss the EDP stages and students' progress working through the EDP. In interviews, teachers described how they saw frequent discussion of the EDP stages as critical for student learning. For example, when asked how often he explicitly discusses the EDP with students, Neil responded:

> *All the time. All the time. If you try to refer it and use the terminology and the verbiage, 'this is part of understand', 'this is part of identify', 'this is part of prototyping', Things like that. So we're trying to reinforce it and bring it up as much as possible.*

Observation data confirm that teachers often engage in discussions detailing expectations for student activity at each EDP stage and documentation of EDP progress in the curricula' s Engineering Design Process Log (EDPL). Often, these discussions occurred at the beginning of class before "turning students loose" to work on their own. For instance, Sally began one 7th-grade class session with the following overview of expectations for the class period:

> *In your EDPLs, everyone should have Identify done, Understand done, you should have your wing design, as well as your groups' wings designs, in Ideate. Next, you have to Evaluate - take those requirements and concepts (have at least 3 ideas to look at, including you and your group members'), then add a reflection and decide on likely or unlikely to succeed. After you've done that, you are going to move on to prototype - add the wing design you chose and save it. Make sure you are caught up with your EDPL.*

Finally, in addition to specific discussions of the EDP as students complete design challenges, efficient facilitators of the EDP were much more likely to discuss the purpose and nature of engineering with their students. In some instances, these discussions occurred within the context of student work on design challenges. For example, in one observed interaction, an 8th-grade student in Neil's class expressed uncertainty about his leg design, stating, "I don't know if it's going to work". In response, Neil highlights the iterative nature of the EDP, stating, "remember, engineering isn't 'one and done'. It may work. It may not. What matters is that you are thinking about why so you can use that info to improve your design. That's what you'll talk about in your prototype analysis, what worked and what didn't." The next day, the student returns to the teacher after his robot failed to navigate the test course, asking, "If it doesn't work, does that mean we get a bad grade?" Neil then reiterates the importance of analyzing prototype performance, drawing a connection to experimentation in science, "just like when you do a science experiment, it's about the explanations you give about your design and how you analyze the performance of the design. It's all about that analysis, not whether it worked. Not *if* it worked, but can you analyze *why* it didn't work or not? Just like in science."

In other instances, teachers expounded more generally about engineering, drawing connections to contexts beyond the STEM-ID design challenges. For example, Sally concludes a final 8th-grade class session of the semester by expressing her hope that students have developed a new appreciation for the EDP:

> *I hope you leave understanding the engineering design process and how it helps identifies the problem think of different ways to come up with solutions. You can use this process in a variety of things you do. I hope you realize engineering is more than you think - designing shoes designing watches is a type of engineering, engineers have a variety of skills.*

In a subsequent 7th grade class, Sally concludes the semester by telling students that "the goal of the class is for students to understand the engineering design process and how they can be applied in solving problems", encouraging students to continue applying the EDP to their everyday lives:

> *Every time you have a problem you identify, think about what the problem is and think of different strategies. Being able to go through the steps of brainstorming solutions and trying them out, and iterating and adjusting them constantly to get to solutions is a huge skill you can use in many facets of your life.*

In these examples, Sally not only draws students' attention to the "many facets" of their lives where the EDP is applicable but spontaneously references several of the steps of the process (problem identification, ideation, prototyping, and testing), thus underscoring both the relevance of the EDP generally as well as the practical utility of its individual stages.

VI. Discussion

Both from our work with engineering teachers and accounts in the literature [7], we know that facilitating the EDP can be quite challenging. Given the limited time and resources in K-12 schools, it is not uncommon for teachers to fail to complete or even reach the culminating design challenges that typically occur toward the end of engineering curricula. Our data provide some indications of pedagogical tendencies that may set teachers who are able to successfully lead students through the complex process of conceptualizing, evaluating, prototyping, and testing solutions to design problems apart from teachers who struggle to do so. Within the context of our project and implementation of the STEM-ID curricula, efficient EDP facilitation is characterized by the tendency to foster meaningful, continuous engagement as students work at multiple stages of the EDP, providing a "roadmap" for navigating the EDP through frequent, explicit discussion of the EDP stages, and reinforcing the "why" of working through the EDP through meaningful discussions of the nature of engineering and the relevance of the EDP to students' everyday lives. Our data suggest a need to infuse professional learning with opportunities for teachers to learn and practice strategies for efficient facilitation of the EDP. At the same time, as teachers develop or discover new strategies that work for their EDP facilitation, we see great value in providing opportunities for engineering teachers, who are often isolated as the lone engineering teacher at their schools, to share and jointly reflect on their experience within professional learning communities.

Interestingly, although teachers did describe becoming more effective, efficient facilitators of the EDP over time, the tendencies we identified were not always related to engineering teaching experience. Indeed, our most efficient facilitator of the EDP (Sally) began participating in our project during her first year teaching engineering, and the two teachers who struggled the most with EDP facilitation were veterans with several years of experience teaching engineering. At the middle school level, as is the case in our project, teachers come to engineering from various backgrounds with various degrees of experience with engineering. As our project moves forward, working with teachers from diverse backgrounds, we plan to continue examining specific practices linked to successful EDP facilitation as well as teacher characteristics, such as pedagogical content knowledge (PCK), organizational and time management skills, and self-efficacy, that may influence how teachers approach the EDP. As indicated by previous studies, effective teaching encompasses more than just expertise in the subject matter. It involves a diverse range of knowledge and skills, including content knowledge, general pedagogical knowledge, curriculum knowledge, pedagogical content knowledge, understanding of learners, knowledge of educational contexts, and awareness of educational goals and values [10, p. 348]. Furthermore, teaching self-efficacy is connected to the teaching of engineering design and the belief in one's ability to impart knowledge of engineering design effectively [18]. Hence, it is essential to thoroughly examine these teacher characteristics due to their significant impact on student learning.

While we hope that this work may inform similar efforts, it is not without limitations. The data presented here provide insight into the experiences of one group of teachers using one set of engineering curricula to facilitate the EDP. As is the case in all qualitative research, the results cannot necessarily be generalized beyond the particular context of this study. Additionally, although our observation dataset was robust, spanning over 100 class sessions, nearly all of which afforded the opportunity to observe EDP facilitation, unevenness in the data and constrained timing of the majority of observations within a two-week period mean that we necessarily have an incomplete picture of EDP facilitation across teachers. There may be additional tendencies and strategies deployed by teachers that were not captured by our data collection.

VII. Conclusion

There is an array of teacher characteristics and contextual factors that inevitably influence how the EDP unfolds in an engineering classroom. In the current study, by identifying tendencies we observed among teachers who efficiently implemented the EDP, we hope to provide insight that may inform engineering curriculum and professional development projects more broadly. For example, highlighting the frequency with which efficient facilitation meant managing student activity across multiple stages of the EDP instead of engaging students in lockstep, the closely managed process suggests a need for professional learning experiences that help teachers develop the skillset required for this approach. Similarly, illustrative examples of teachers engaging students in explicit discussions of EDP progress and the nature of the engineering suggest a corresponding need for explicit inclusion of these strategies in curricula and professional development.

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