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Preservice Elementary Teachers' Engineering Design During a Robotics Project

Jiangmei Yuan
West Virginia University

ChanMin Kim
Pennsylvania State University

Lucas Vasconcelos
University of South Carolina

Min Young Shin
The University of Georgia

Cory Gleasman
Tennessee Tech University

Duygu Umutlu
Boğaziçi University

Engineering design provides students with an authentic context to apply science and mathematics to solving problems and motivates them to learn science, technology, engineering, and mathematics (STEM) subjects. Thus, teachers need to experience and become familiar with engineering design. However, little is known about how preservice teachers learn to do engineering design work. This study examined the engineering design practices of preservice teachers as they worked on a technology-enhanced design activity. The authors video-recorded a group activity in which preservice teachers designed, built, and programmed robots and then analyzed their discourse using verbal protocol analysis. The authors examined what design activities were practiced and how they were practiced and analyzed design-related conversational moves, which yielded an understanding of how preservice teachers collaboratively constructed knowledge during their engineering design process. The findings showed that preservice teachers frequently generated ideas to solve problems and evaluated their ideas. Their least frequent activities were judging the feasibility of solutions and modeling. Furthermore, they seldom disagreed with their partners after an idea was generated. Suggestions for preparing preservice teachers to incorporate engineering design into K-12 classrooms include providing engineering design opportunities, exposing preservice teachers to design examples, and creating design tasks that require the application of science and mathematics knowledge.

Engineering education at the K-12 level has been emphasized in many countries, including the United Kingdom, the United States, and Australia (Purzer et al., 2015). Many states in the United States have included engineering in their K-12 standards (Dare et al., 2014).

Engineering, as a discipline itself, is important because of the need for engineers in the 21st century (Parker et al., 2020). Engineering is also a vehicle for science and mathematics learning, as engineering design projects provide students with opportunities to apply science and mathematics knowledge to problem solving (Roehrig et al., 2012). In particular, engineering design plays a key role in science education. The National Research Council (2013) elevated engineering design "to the same level as scientific inquiry in science classroom instruction at all levels" (p. 337).

Engineering is often used as a vehicle to motivate students to learn science, technology, engineering, and mathematics (STEM) subjects and pique their interest in pursuing STEM careers in the future (Chiu et al., 2017). Elementary school years are particularly critical for students to develop their STEM interests (Kaya et al., 2017; Yuan et al., 2019). However, incorporating engineering in the K-12 curriculum is challenging for elementary teachers. Effective inclusion of engineering in K-12 curriculum requires three-dimensional teaching, where engineering core ideas, engineering practices, and cross-cutting concepts are knit together (Purzer, 2017).

Three-dimensional teaching requires teachers to take the role of design coaching, guiding student thinking, and responding appropriately to unanticipated approaches students adopt (Purzer, 2017). Most elementary teachers have not received formal engineering learning or training on three-dimensional teaching, and design coaching posits extra challenge. Providing preservice teachers with training on how to incorporate engineering design into K-12 curriculum will benefit these teachers and their future students. To design and implement effective training, teacher educators need to understand where preservice teachers are in their own development of engineering design practices. This study examined early childhood and elementary education preservice teachers' engineering design practices when they engaged in a technology-enhanced hands-on design project.

Relevant Literature

Engineering Design

Engineering design is a process engineers go through when designing solutions (Hynes, 2012). It is generally considered to consist of steps including defining problems, gathering information, generating ideas, modeling, analyzing whether the potential solution works, evaluating the solutions, making decisions, and communicating about the design with others (Moore et al., 1995). These steps fall into three stages – problem scoping, developing alternative solutions, and project realization.

Engineering design is iterative, and engineers do not go through the steps in a linear manner (Adams et al., 2003). At any point in the process, designers may go back to an earlier step. For example, a team of designers may brainstorm some solutions and evaluate them. They may then gather more information after realizing the need for more information to better understand the problem. Another feature of engineering design is that design problems tend to have multiple solutions (Hynes, 2012). Thus, when practicing engineering design, designers also engage in problem solving (Hirsch et al., 2001).

Importance of Engineering Design in Science Education

One of the main goals of K-12 engineering education is to help students learn and practice engineering design (Marshall & Berland, 2012; Martin et al., 2015). Engineering design is central to professional engineering, so design-focused engineering education aligns learning at school with the experiences of engineers (Berland et al., 2014) and prepares engineers for the future (Cardella et al., 2008). Engineering design activities provide students with an authentic context to apply science and mathematics to problem solving (Wendell, 2014).

Being able to connect science and mathematics, engineering design is often used as a vehicle for integrated STEM education (Guzey et al., 2017). In particular, engineering design is important for science education, as indicated in policy documents that call for an emphasis on design-based learning. For example, the *Next Generation Science Standards* highlight engineering practices and concepts as key components of science education (National Research Council, 2013).

Research documents students' knowledge gain from participating in engineering design activities and reveals the important role of design-based engineering learning in STEM education, particularly science education. For example, Burghardt et al. (2010) found that middle school students engaging in a bedroom design curriculum performed better on a mathematics knowledge test than those involved in a typical mathematics curriculum.

Many studies demonstrate the contribution of engineering design to students' science learning. For example, Wendell and Rogers (2013) found that students learning robotics and engineering design demonstrated significantly higher science learning gains than those learning regular science units. Guzey et al. (2016) demonstrated that special education students' life science knowledge substantially increased and students' attitudes toward STEM subjects significantly improved after participating in an engineering-design based curriculum.

Preparation to Teach Engineering Effectively

The nature of engineering design and the effective approach to facilitating engineering design-based learning make it necessary for elementary teachers to learn how to incorporate engineering design into K-12 classrooms. Specifically, engineering design problems are complex and ill defined, and the design process is iterative. Multiple solutions and solution pathways to design problems can be found. These features of engineering design problems and design process pose challenges for teachers (Radloff & Capobianco, 2019; Watkins et al., 2021).

Also, knitting together the teaching of engineering core ideas, engineering practices, and cross-cutting concepts, three-dimensional teaching is an effective approach to design-based learning (Purzer, 2017). Three-dimensional teaching requires teachers to be design coaches who elicit, notice, and respond to students' engineering design thinking. However, most elementary teachers do not experience formal learning of engineering design and its integration into classrooms through such effective approaches as three-dimensional teaching and design coaching.

Learning From Engineering Design via Robotics

Manipulatives can scaffold student understanding of abstract concepts (Bers & Portsmore, 2005). Educational robotics, involving digital manipulatives with computing capacity, has been used to support STEM learning because it can increase students' interest in STEM subjects (Rogers & Portsmore, 2004) and provide students with opportunities to apply STEM knowledge and thus improve content learning (Barker & Ansorge, 2007; Highfield, 2010; Kaya et al., 2017; Whittier & Robinson, 2007). Also, it has been used for preservice teachers' learning of STEM education (Kim et al., 2015, 2018; Yuan et al., 2019).

In particular, robotics lends itself to teaching engineering to K-12 students. The engineering elements such as motors and sensors, as well as building blocks and coding, enable educators to quickly create an engineering intervention (Rogers & Portsmore, 2004). The computational nature of robotics enables access to immediate feedback, which is conducive to the development of students' problem-solving skills (Sullivan & Heffernan, 2016).

Robotics has been used to teach engineering in K-12 classrooms (e.g., Cejka et al., 2006; Jackson et al., 2017; Rogers & Portsmore, 2004). Research shows that robotics competitions increase students' interest in engineering design (Ayar, 2015) and in pursuing an engineering major (Melchior et al., 2005). The efforts made to bring engineering to K-12 classrooms by engaging students in building and programming robots enhance students' engineering literacy (Cejka et al., 2006), boost their confidence about basic engineering concepts (e.g., sensors, structural stability, and gears; Taban et al., 2005), and build an array of skills (e.g., teamwork, critical thinking, and problem solving) that are critical to engineering careers (Benitti, 2012).

Purpose of Study

We examined early childhood and elementary education preservice teachers' engineering design practices when they engaged in a technology-enhanced hands-on design project. For teachers, "understanding the engineering design process is important in order to understand and implement effective teaching of design courses" (Lemons et al., 2010, p. 288). Teachers need to provide students with engineering design scaffolding, guide students, and respond appropriately to unanticipated approaches adopted by students (Purzer, 2017). All of these elements require teachers to become familiar with and experience engineering design.

We expected that this study would inform methods of preparing teachers to integrate technology-enhanced engineering design experiences into classroom practice. Wendell (2014) explored the most and least frequent design activities and design-related conversational moves of preservice teachers' design of furniture for characters in children's literature. Epistemic tools can facilitate knowledge construction when students engage in activities that focus on engineering concepts and practices (Kelly & Cunningham, 2019). Understanding how preservice teachers learn to do engineering design while working on technology-enhanced design activities can be beneficial for the teacher education community. Because educational robotics lends itself to teaching engineering and it has been used to bring engineering to K-12 classrooms, we examined the process of preservice teachers' design, assembly, and programming of robots and how they practiced design activities.

An analysis of design-related conversational moves can help researchers understand preservice teachers' process of solving engineering problems. Engineering design is "a social process of negotiation and consensus" (Bucciarelli, 1994, p. 21). Engineering is a "team sport" in which "collaboration leverages the perspectives, knowledge, and capabilities of team members to address a design challenge" (National Research Council, 2010, p. 45).

In addition, design involves a large number of decision points (Crismond & Adams, 2012). To make joint decisions, people need to recognize, accept, or refuse their group members' communicative intentions, which are coconstructed through conversational moves (Macagno & Bigi, 2017). Thus, discourse, in particular conversational moves, helps groups construct knowledge during engineering design. Conversational moves are different types of initiations (setting up a discourse expectation about what will follow, such as explaining something) and responses (fulfilling the expectations set up by initiations, such as a "yes" reply) that serve to fulfill the purposes of the dialogue (Carletta et al., 1997; Gervits et al., 2016a).

We were also interested in which design activities that were practiced more frequently than other design activities, because a common way to characterize engineering design is to see the emphasis placed on various steps (e.g., Cardella et al., 2008; Roberts et al., 2007; Stempfle & Badke-Schaub, 2002). Observing which design activities preservice teachers engaged in the most can yield an understanding of what they emphasized in their design thinking. The following research questions were addressed:

1. What design activities and design-related conversational moves were practiced?
2. How were the design activities practiced?
3. Was there any design activity or design-related conversational move practiced more frequently than others? If so, what were its associated characteristics?

In the research questions, to practice means to engage in or to do design activities or related conversational moves, which we did to study what preservice teachers did to gain proficiency in engineering design.

Theoretical Framework

Our work was guided by a situated learning framework (Johri & Olds, 2011; Lave & Wenger, 1991). This perspective asserts that learning is social and knowledge is constructed through participation in sociocultural practices of a community. Since one of the central goals of engineering education is to enable learners to become a part of the community of engineers, it is important that preservice teachers engage in practices of the community in a collaborative way. These practices include defining problems, generating multiple solutions, evaluating solutions, making decisions, and so forth (Atman et al., 1999; Cunningham & Kelly, 2017). Therefore, we provided preservice teachers with an opportunity to engage in these practices and obtained an understanding of their practices. As discourse is important for the development of a community of practice (Burbules, 1993), we examined preservice teachers' discourse during engineering design to achieve such an understanding.

Methods

Research Context and Participants

This study was part of a larger project in which early childhood education majors engaged in robot building and programming as well as STEM teaching for young children. This course included a variety of making activities with an emphasis on hands-on learning, including problem solving and designing, construction, and testing of prototypes. Example exercises participants completed included using index cards to build structures and testing the structures, designing and constructing a vehicle to carry and protect Humpty Dumpty as he descended the designated ramp and crashed into a barrier, and examining and critiquing Engineering Is Elementary (https://www.eie.org) activities and TeachEngineering (https://www.teachengineering.org) curricular units.

The focus of the present study was the robotics learning module, in which participants built and programmed robots, designed a lesson plan, and created a poster to present their group robots and lesson plans to elementary teachers (see details in the Robotics Learning Module section). The robotics learning module was codesigned by the course instructor and the research team within the scope of the course objectives.

Participants were six preservice teachers from the course who agreed to participate in the study and had complete datasets. All participants were female, and their average age was 19.67 (*SD* = 0.75). Four participants were White, one Asian, and one African American. Half of the participants had completed four semesters at the university prior to their participation in the present study. One participant had completed one semester and two had completed two semesters. Participants' names are pseudonyms.

The Robotics Learning Module

RoboRobo was the robotics platform used in this study. RoboRobo allows several types of robot design and programming that vary based on levels of difficulty. Each kit includes a box with parts that can be used to build robots and a manual that guides users through different levels by providing assembly instructions and programming practice activities. The higher the level, the more complex the robot assembly and programming.

The undergraduate class met for 75 minutes on Mondays and 135 minutes on Wednesdays. Three weeks were allocated to the module, meaning that participants worked on the module for about 10 hours. The robotics learning module consisted of three parts: (a) the instructor's introduction of educational robotics, RoboRobo kits, and the Rogic program (the block-based programming environment of RoboRobo), (b) participants' individual practice of assembling and programming robots, using the Level 1 kit, and (c) a group project where participants built and programmed an advanced robot, designed a lesson plan around it, and created a poster to present their lesson plan to a group of elementary teachers.

During Part 1, the instructor introduced educational robotics as a tool to promote STEM education. What followed was an introduction of the major components of RoboRobo kits, including motors, the Infrared Receiver (IR) sensor, the central processing unit (CPU) board, and the light-emitting diode (LED) lights, among others. Subsequently, the instructor demonstrated the functions of the major code blocks by asking participants to run four programs and going through one of the four programs line by line. Part 1 was about 75 minutes long.

During Part 2 of the learning module, each participant individually used a Level 1 kit to assemble and program a robot to perform four tasks. An example task was to turn on the three LED lights one by one and have each light stay on for a predetermined number of seconds. Level 1 activities are considered the least complex in the robotics kit. The instructor provided assistance as needed to those who struggled with robot assembly and programming during Parts 2 and 3. Participants spent approximately 120 minutes individually assembling their robots and 120 minutes programming their robots.

During Part 3, participants worked with a self-selected partner on a robot design project, created a lesson plan, and presented their project to a group of elementary teachers. The design challenge was to build an advanced robot that participants could develop lesson plans around. The advanced robot could be one that came from Level 2 or participants could design their own.

The group robot was required to be an advanced robot, compared with the individual robots they had already built and programmed. This was one criterion the instructor specified. The constraint the instructor set up was that the groups had to design a robot to align with a lesson plan idea. As "professional development for teachers of engineering should make clear how engineering design and problem solving offer a context for teaching standards of learning in science, mathematics, language arts, reading, and other subjects" (Reimers et al., 2015, p. 42), the instructor emphasized that the lesson plans should address standards of STEM, English language arts, or other subjects.

Data Collection

Data collection was conducted upon approval from the university's Institutional Review Board, and participants' informed consent was obtained prior to the robotics learning module start date. Participants' group activities of designing, assembling, and programming robots during Part 3 of the learning module were video recorded. Each pair was recorded separately, and each pair's video was approximately 150 minutes long.

Data Analysis

This study used verbal protocol analysis, a method considered to be the most appropriate to study design thinking (Dinar et al., 2015; Lemons et al., 2010). It has been used extensively since the 1970s to understand how engineers develop solutions to engineering problems (e.g., Atman & Bursic, 1998; Lemons et al., 2010; Waldron & Waldron, 1988). Expert or student designers are audio or video recorded during or after engineering design (Hay et al., 2017). The analysis of the transcriptions of the recordings can provide an understanding of the processes used to solve engineering problems.

We analyzed the videos following these steps. First, we transcribed the videos verbatim. We then read half of one team's transcript and discussed how to refine the coding scheme. We independently analyzed a 20-minute video in which participants designed and assembled their robots. We resolved our analysis discrepancies to reach a shared understanding of the coding scheme and video analysis. Then we independently conducted further analysis. Cohen's Kappa coefficient was .73. If any portion of the video transcript was confusing, we watched the video to ensure a thorough understanding of the transcript.

The coding scheme included engineering design activity codes and design-related conversational move codes (see Appendix), which were applied simultaneously to the transcripts during analysis. The engineering design activity codes were adapted from Atman et al.'s (1999) coding scheme, which has been commonly used to analyze engineering design activities. For example, the coding scheme was used to compare the design practices of individual senior and first-year engineering students, compare the design processes of engineering students and experts (Atman et al., 2007), and examine the changes in engineering students' design as these students advanced from freshmen to seniors (Cardella et al., 2008).

The coding scheme was also applied to group design. For example, it was used as a framework to characterize undergraduate students' group design (Roberts et al., 2007; Swenson et al., 2014), compare the group design processes of students in the United Kingdom and the United States (Yasar et al., 2008), and examine the engineering design practices of preservice teachers as they designed furniture for a character in a children's book (Wendell, 2014).

The following adaptations were performed to Atman et al.'s (1999) code. We deleted two codes: (a) "identify need," because there was no need for participants to state the reasons for design, and (b) "communication," because participants communicated about the design with their teammates throughout the design process, similarly to Roberts et al. (2007). We changed the code "implementation" to "making" to better reflect the hands-on component of the robotics project (i.e., putting the robot pieces together and connecting the robot motor to the right port).

We used the design-related conversational move codes from Wendell (2014) and also referred to the conversational moves in Carletta et al.'s (1997) coding scheme. Specifically, we added the code "respond" to Wendell's conversational moves codes. When participants made a response that did not simply show agreement or disagreement, it was coded as "respond." For example, one participant asked, "Do we have buttons, or do we have a remote control?" Her partner responded by saying, "Remote control." Another code we added was "respond to instructor," which refers to participants' responses to the instructor when he asked questions about their problems or design.

Results

Each of the three pairs designed, built, and programmed a robot. The team of Harper and Camila worked on a Level 2 robot, a motorcycle named Harley. It could move forward and backward and turn left and right. Anne and Lisa built a revised version of a Level 2 robot (grab bot) by adding traffic lights to it. They named their robot Safety Bot. Safety Bot could grab things and carry them around. It also had a buzzer to get children's attention. Evelyn and Mia's robot was named Wall-e, also a Level 2 robot. It could move forward and backward.

Harley and Safety Bot were controlled by a remote controller, a Level 2 function. The remote controller had five channels, each of which controlled a particular performance, including making a robot go forward and backward, turn left and right, and back up. The following sections present the design activities and design-related conversational moves participants practiced, how the design activities were practices, and the associated characteristics of the most frequent design activities.

Design Activities and Conversational Moves

Participants' discussion on design activities accounted for 31.96% of the speech; conversational moves were 19.16%; discussion on making (hands-on work including assembling, programming, and decorating robots) was 37.83%; finally, 11.05% of the participants' speech was categorized as "other" (see Table 1). Participants practiced *all* design activities. The most frequent engineering design activity was generating ideas to solve problems, which accounted for 33.33% of the total number of design activities.

Participants generated ideas to design, assemble, and program their robots. For example, after Anne and Lisa decided to make their own robot by adding traffic lights to the grab bot described in the Level 2 manual, they discussed how to assemble their robot. Anne said,

> So what if we take this design [the design of the grab bot in the Level 2 manual] of how they build everything with CPU [Central Processing Unit] and the wheels, but take off all the extra parts that we don't want. This is the grab bot. We don't really want to grab, so we have to add those pieces [traffic lights they discussed earlier] to it. Then we can just add our race and ideas.

Table 1
The Frequency and Percentage of Each Design Activity and Conversational Move

Code	Frequency	Percent
Design Activities	327	31.96%
Problem Definition (PD)	35	10.70%
Gathering Information (GATH)	67	20.49%
Generating Ideas (GEN)	109	33.33%
Modeling (MOD)	13	3.96%
Feasibility Analysis (FEAS)	3	0.92%
Evaluation (EVAL)	79	24.16%
Decision (DEC)	21	6.42%
Conversational Moves	196	19.16%
Revoicing (REV)	27	13.78%
Requesting (REQ)	28	14.29%
Agreement (AGR)	71	36.22%
Disagreement (DIS)	6	3.06%
Respond (RESP)	22	11.22%
Respond to Instructor (RtI)	42	21.43%
Making	387	37.83%
Other	113	11.05%
Total	1023	

Evaluating a solution also occurred frequently, which was 24.16% of the total number of design activities. An example of evaluating a solution was that after Camila and Harper programmed their robot, Camila ran the code. Harper said, "The handlebar just turned." Camila then added, "I think that's the wrong thing."

The least frequent design activity was judging the feasibility of a solution – whether a potential solution would solve the problem (0.92%). The following exchange, in which Harper and Camila discussed which robot to build, is an example of judging the feasibility of a solution. As seen in Line 1 (L1) of the transcript, Camila said they could build a jet bot. Harper added that they could do another robot (L6). Camila (L7) commented on the feasibility of building and programming the robot by saying, "That one looks really easy."

> 1. Camila: The Jet Bot?
>
> 2. Harper: Because it looks cool, but I really don't care. I don't like this one. [Pointed to another robot in the manual.]
>
> 3. Camila: [Looked at partner's computer screen.] Me either. I want to do either that one [jet bot] or.
>
> 4. Harper: Or Wall-e? This one?
>
> 5. Camila: Or that one [Wall-e].
>
> 6. Harper: Or this one? [Pointed to another robot in the manual.]
>
> 7. Camila: That one looks really easy.

The second least frequent design activity was modeling (3.96%). When participants engaged in modeling, they detailed how to develop a problem solution, including estimating something and making a part fit into the design. One example is an excerpt in which Evelyn said she was not able to add the wheel frame to the robot and asked Mia whether their robot needed the wheel frame. Mia responded, "Yeah, we still need it. This part [part of the wheel gear] is sticking out. That's for this [a robot part in Mia's hand] to be connected to it."

Twenty percent of participants' discourse was devoted to design-related conversational moves. The most frequent conversational move was expressing agreement with a partner's ideas, which was 36.22% of the total. For example, after finishing assembling their robot, Anne and Lisa discussed what they wanted their robot to do. Anne said, "We definitely want it to go forward." Lisa responded, "Yes."

The second most frequent conversational move was responding to the instructor while they were seeking help from the instructor (21.43%). An example of responding to the instructor is an excerpt in which Evelyn was trying to connect motors to their team's robot, but she seemed to run into an issue. She asked the instructor, "Why does the left motor only have two and right motor have three?” The instructor answered, “Maybe you put a stepper motor on instead of a regular motor.” Evelyn then checked the motor and responded, “Yes, we did.”

Showing disagreement was the least frequent conversational move (3.06%). An example of showing disagreement is when Camila added the main frame to her team’s robot and showed it to her teammate Harper, who then said, “But the back part goes this way, to this motor. [Showing the manual] You see? That flipped, like the other way.” Camila disagreed: “No, it’s this way.”

The second least conversational move was making a response to a teammate that did not simply show agreement or disagreement (11.22%). For example, Harper and Camila were about to program their robot. Harper asked, “Do we have buttons [to control the robot] or do we have a remote control?” Camila responded, “Remote control.”

How Design Activities Were Practiced

The most frequent design activity was generating ideas. When designing their robots, participants were able to generate multiple ideas. In the passage that follows, Anne and Lisa discussed what they wanted their robot to do when each of the five buttons on the remote control was pressed.

> 8. Anne: It will still have this body [pointing to the manual on her computer], but you say use tracks instead. I wish we could do something like, it can be a race bot, but instead of red [LED light] makes it stop, yellow [LED light] slows down, and green [LED light] goes fast, it’ll like, light up, you know.
>
> 9. Lisa: Yes, and then with the button thing, it can be like. It’s red, and then it completely stops for the red light lighting up. And then let’s say this yellow, light up yellow, and then go slow. Green, it will speed up.
>
> 10. Anne: Yes. We can also do, when you turn it on, kind of how we did the other robot [the robot they programmed individually], when we turned it on, the lights, each light goes red, then yellow, then green, and then beep. That can be, get it to say go, beep. And then, you want it to go fast, then the green light.
>
> 11. Lisa: That’ll be about it. And then you can [unintelligible].
>
> 12. Anne: [unintelligible], but I do like that idea.

When programming their robots, participants generated one idea at a time, revised their program, and evaluated the idea by running the program to see whether it worked. For example, when Camila and Harper finished programming their robot, Camila ran the program. Their robot moved, and she was happy with it. However, Harper said, “If it’s backwards, that’s right. If it is forwards, that’s wrong. Do you get what I am saying?” Camila revised and tested the code. In the follow dialog, they discussed the evaluation result, generated more ideas, revised the code, and evaluated the ideas by running the code.

> 13. Harper: Do you see what I mean? [She was implying that the robot didn't run as they wanted it to.]
>
> 14. Camila: Okay, I think it would make more sense if I make it go forward. I'll show you. [She worked on the program and then tested the robot.] That's moving backwards.
>
> 15. Camila: [Generated another idea, worked on the program, and then tested the program again.] It is going the right way, right?
>
> 16. Harper: Yeah, yeah, yeah.

The second most frequent design activity was evaluating solutions. When assembling their robots, the products participants built enabled them to do the evaluation. They also referred to the manual to evaluate what they assembled. In the following dialog, Evelyn looked at what her partner Mia assembled and said the eyeballs were backwards. Mia then checked the manual and agreed with Evelyn.

> 17. Evelyn: [Looked at the parts her partner assembled.] These eyeballs are backwards
>
> 18. Mia: [Looked at the manual.] Yeah. Wait, I assembled it exactly the way as it said.
>
> 19. Evelyn: I think the arms are just backward.
>
> 20. Mia: No, the arms are fine. Just eyeballs. [Checked the manual.] I'm gonna have to – [Seemed to generate an idea. Disassembled the eyeballs and assembled them in another way.]

When participants programmed their robots, they evaluated their ideas by running the code, which provided them with immediate feedback on whether the solution worked. In the example in Lines 13-16, Camila ran the code after they finished programming their robot. Harper made the statement, "If it's backwards, that's right. If it is forwards, that's wrong. Do you get what I am saying?" The team then generated ideas to revise the code. Once they developed an idea, they revised the code, and then evaluated their idea by testing the robot.

Characteristics Associated With the Most Frequent Code

To explore the associated characteristics of the most frequent design activity, we counted the occurrences of design activities and conversational moves following the generation of an idea. As shown in Table 2,the most frequent activity that followed was showing agreement with an idea (27.21%). Making also occurred frequently (13.61%). Considering participants' design activities and design-related conversational moves, most of the time, they were generating ideas, expressing agreement with their partners' ideas, or implementing their ideas.

Table 2
Codes Following the Most Frequent Design Activity (Idea Generation)

Code Following Idea Generation	Frequency	Percent
Design Activities		
Problem Definition (PD)	1	0.68%
Gathering Information (GATH)	0	0%
Generating Ideas (GEN)	19	12.93%
Modeling (MOD)	0	0%
Feasibility Analysis (FEAS)	1	0.68%
Evaluation (EVAL)	6	4.08%
Decision (DEC)	2	1.36%
Conversational Moves		
Revoicing (REV)	7	4.76%
Requesting (REQ)	17	11.56%
Agreement (AGR)	40	27.21%
Disagreement (DIS)	5	3.40%
Respond (RESP)	10	6.80%
Respond to Instructor (RtI)	0	0%
Making	20	13.61%
Other	19	12.93%
Total	147	

Discussion

This study examined early childhood and elementary education preservice teachers' engineering design practices when they engaged in a technology-enhanced, hands-on robotics design project. Study findings show that hands-on work (i.e., putting the robot pieces together and programming and decorating their robots) accounted for about one-third of preservice teachers' discourse, design practices about one third, and design-related conversational moves a little less than a quarter. The rest were not related to the project. Preservice teachers generated many ideas to solve problems. The hands-on project enabled them to evaluate their ideas frequently. The least frequent engineering design practices were judging the feasibility of solutions and modelling. They seldom disagreed with their partner after an idea was generated. Major findings are discussed next.

The most frequent design practice in this study was generating new ideas. This result is consistent with the finding of a study that examined preservice teachers' design of a piece of furniture (Wendell, 2014). What contributed to preservice teachers' generation of many ideas in this study may have been their exposure to design examples and previous practices. Preservice teachers were provided with a manual, including possible robots that could be built, step-by-step instructions on how to build the robots, and programming exercises. In addition, before preservice teachers designed and programmed their group robots, they practiced individually building a robot and programming the robot to perform four tasks set by the instructor.

Examples and practice can be helpful, since designers tend to depend on existing designs that are documented or recalled and modify them to solve their problems (Sarkar & Chakrabarti, 2017). The ideas designers have been exposed to can trigger more idea generation (Perttula & Sipilä, 2007). Exposure to examples or ideas and engineering design experience seem important for developing solutions for design problems.

One characteristic of preservice teachers' idea generation was that when programming robots, they tended to generate one idea, program their robots, and run the code to evaluate the idea. This pattern suggests that preservice teachers used a coupled decision-making process, in which they generated one idea at a time and then evaluated the solution, deciding to adopt the solution or generate new ideas based on the evaluation (Dwarakanath & Wallace, 1995). This finding is aligned with abductive reasoning observed during tinkering among early childhood preservice teachers (Kim et al., 2021).

One possible reason for the coupled decision-making was that novice designers found the act of producing multiple solutions in parallel (i.e., generating several alternative solutions at a time and comparing them to make decisions) to be challenging (as found by Daly et al., 2011). The other reason could be that the immediate feedback received from running the code enabled them to evaluate solutions frequently and hence use the generation-evaluation iteration.

The hands-on project enabled preservice teachers to evaluate their ideas frequently. Evaluating solutions was the second most frequent design activity, which differed from Wendell's (2014) study, where preservice teachers seldom evaluated their solutions. The preservice teachers in Wendell's study designed a piece of furniture by creating three-dimensional models and sketches without building the furniture. In the present study, preservice teachers assembled their robots and programmed them to perform tangible movements. Solutions in such physical forms could be evaluated immediately because what they built and programmed could inform them as to whether the solutions worked. This finding related to the hands-on nature of robotics (Rogers & Portsmore, 2004; Taban et al., 2005; Telenko et al., 2016) suggests that robotics can be a promising platform to teach engineering.

Judging the feasibility of a solution and modeling were preservice teachers' least frequent practices. This finding aligns with other studies suggesting that novice designers tend to engage in feasibility analysis much less than experienced designers (Mentzer et al., 2015). However, Wendell (2014) found that the most frequent design practice was judging the feasibility of a possible solution. These differences can be attributed to the nature of the design tasks in the two studies. The preservice teachers in the present study not only designed robots but also assembled and programmed them, whereas preservice teachers created three-dimensional models and sketches of the furniture they designed without actually building the furniture in Wendell's (2014) study.

Specifically, Table 2 shows that immediately after an idea was generated, most of the time, the team agreed on the idea or implemented the idea to build, program, or decorate robots. The main goal of engineering design is to create something that works (King & English, 2016). Once they found that the solution worked by implementing it, the preservice teachers in the present study may have then continued to work on other aspects of the project. When they discovered that the solution did not work, they generated more ideas. They implemented the ideas to build and program their robots rather than think about the underlying science and mathematics knowledge and use the knowledge to judge the feasibility of the ideas.

Studies have shown that novice designers tend not to apply science and mathematics knowledge to engineering design. For example, in one study (Berland et al., 2013), high school students worked on engineering design projects for two semesters. They reported in interviews that they rarely used science concepts and principles or mathematics calculations when making design decisions.

The most frequent conversational moves were showing agreement and asking partners for clarifications to better understand ideas (as shown by the code "requesting"), which helped preservice teachers collaborate effectively by developing common ground (Gervits et al., 2016b).

Preservice teachers seldom disagreed with their partner's ideas. As described earlier, preservice teacher participants seemed to prefer to implement the generated idea immediately rather than discuss whether the idea would work or not. Possibly, since the main goal of engineering design is to create a product that works (King & English, 2016), these preservice teachers simply wanted to create a workable robot. After an idea was generated, they wanted to use the idea for their project, instead of generating further options.

Suggestions for Teacher Education

Teacher educators need to provide more opportunities for preservice teachers to be engaged in engineering design (Bull et al., 2009). These engineering design activities can help preservice teachers realize the multiple-path problem solving process and use it later in the role of teacher-as-designer, designing instruction for their students. Preservice teachers can also use their design experience to spark their students' interest in engineering (Zarske et al., 2017). When preservice teachers work on engineering design activities, design ideas and examples, especially common ideas, can be provided, since a larger number of common ideas can better promote the generation of possible solutions than a smaller number of unusual ideas (Perttula & Sipilä, 2007).

Empirical studies show that opportunities are available for professional learning on how to teach engineering for in-service teachers (Duncan et al., 2011; Ficklin et al., 2020; Guzey et al., 2014; Lottero-Perdue & Parry, 2017; Martin et al., 2015; Singer et al., 2016), but few opportunities for preservice teachers. Several models can be used to help preservice teachers gain engineering design experience. First, professional development for particular schools can include preservice teachers who are placed in those schools. Second, engineering units can be built into existing teaching-methods courses to prepare preservice teachers to integrate engineering design into teaching (Kaya et al., 2017). Another model is to provide undergraduate engineering students with training on how to teach engineering to K-12 students, especially how to integrate engineering and science and mathematics (Zarske et al., 2017).

One of the compelling reasons for incorporating engineering into K-12 classroom practice, especially into science and mathematics classes, is that engineering is a vehicle for learning science and mathematics (Wendell, 2014). Moreover, King and English (2016) emphasized that "preparing students to be competent in applying and integrating knowledge from a range of sources to solve an engineering design problem is at the core of a successful approach to STEM integration" (p. 2764). However, in the present study, preservice teachers did not do much feasibility analysis, a design step that provides opportunities for science and mathematics knowledge application (Berland et al., 2014).

One approach is to create engineering design tasks for which science and mathematics knowledge is necessary. For example, preservice teachers can be asked to design a musical instrument, which requires an understanding of vibration, pitch, and volume (Berland & Steingut, 2016), or improve a design (e.g., a prosthetic arm model with weaknesses; Capobianco et al., 2019).

Several other aspects need to be taken into consideration when teacher-education programs prepare preservice teachers to incorporate engineering design into K-12 classrooms. First, to enable preservice teachers to facilitate and assist with their future students' design-based learning, teacher education programs can help them develop adaptive expertise that allows teachers to "function in novel situations" (Martin et al., 2015, p. 36). Challenge-based instruction or a hypothesis-experiment-instruction model can be used for the development of adaptive expertise.

Second, training for preservice teachers needs to be responsive to their cultures by connecting engineering to their experience, knowledge, interests, and values (Mejia et al., 2014) so that preservice teachers do not feel that engineering is foreign to them. Third, for early childhood and elementary preservice teachers in particular, a simplified engineering design process can be modeled, as these teachers may need to use a simplified engineering design model to teach their students (Davis et al., 2017).

Limitations of the Present Study

The findings of this study are limited by the small sample size. Second, the group formation approach may have affected the team dynamics because self-selected teams tend not to examine alternative ideas to build and maintain group solidarity (Davis, 2009). In addition, while this study used typical measures to characterize engineering design practices – counting the frequency of engineering design practices and design-related conversational moves, these measures do not seem to capture a detailed qualitative picture of preservice teachers' engineering design practice (Watkins et al., 2014). For example, these measures cannot yield an understanding of how designers' identification of a particular criterion contributed to solving the problem or how designers make decisions during collaboration.

Future Research Directions

One future study direction is to compare preservice teachers' engineering design practices with those of expert engineers. The comparison of the design processes and practices between preservice teachers and engineers can help educators better understand how to facilitate the development of design proficiencies (Atman et al., 2007). Second, additional research is needed to examine how preservice teachers engage in collaborative decision making, what emotions they experience when struggling with the problems, how they perceive failure, and how they learn from failure. These lines of research can give the field a more detailed picture of preservice teachers' engineering design practices.

Third, in the present study, once preservice teachers generated an idea, most of the time, they implemented the idea by assembling, programming, or decorating their robots and then evaluated the solution. They rarely detailed the potential solution in their discussion and analyzed the feasibility of the solution. However, in the modeling and feasibility analysis steps, designers need to apply science and mathematics knowledge (Berland et al., 2013). These two steps are important for integrated STEM education. Future studies can implement engineering design activities in which design problems cannot be solved without modeling and feasibility analysis.

Last, preservice teachers in this study did little problem scoping. Future research can create engineering design activities in which problem definition is necessary (Wendell, 2014).

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Appendix
Coding Scheme for Engineering Design Activity Analysis (Adapted from Atman et al., 1999; Wendell, 2014)

Code	Meaning	Example
Design Acclivities		
Problem Definition (PD)	Define what the problem is, including stating constraints, identifying criteria, and identifying sub-problems	“Why does this one keep turning like this? Which one is supposed to turn? [Something kept turning]”
Gathering Information (GATH)	Look for information to solve the problem and discuss the information they gathered	**“**[Read the manual] Assemble to the DC motors. Does that take a special screw? Yes. It does
Generating Ideas (GEN)	Generate ideas to solve the problem	“But that means its RC [Remote Control] 2 and it’s not in the 2. I think it’s supposed to be 7.”
Modeling (MOD)	Detail how to develop problem solution. It includes estimating something and making a part fit into the design.	“Yes, but the 2 by 1s [L frames] won’t work because it is supposed to like go through, but it won’t.”
Making (MAK)	Decorate, assemble, and program robots	“Wheel guide… [Kept searching for a proper part to assemble the wheel guide] Is this okay? [Talked to herself]”
Feasibility Analysis (FEAS)	Judge whether the potential solution will work.	That one [robot] looks really easy.
Evaluation (EVAL)	Compare solutions, test a design, and evaluate the results	“I think the arms are just backward.”
Decision (DEC)	Select or eliminate one solution	“Alright. We are going to do the jet bot.”
Design-Related Conversational Moves		
Revoicing (REV)	Restate one’s idea or understanding	Speaker 1: “And then the last one [the last button on the remote control] would be, forward. Because we only have 5 buttons.” Speaker 2: “Forward. The go.” Speaker 1: “So it’s forward, each of the lights, each of the individual lights, and then all three lights.”
Requesting (REQ)	Ask for clarification about an idea or design detail.	Speaker 1: “The left motor, the right motor, and. So the left motor goes to Port 1.” Speaker 2: “In port 1?”
Agreement (AGR)	Agree with a partner	Speaker 1: “We will do recycling. We can make it walk. I’m just saying out.” Speaker 2: “You know… I like it.”

Disagreement (DIS)	Disagree with a partner	Speaker 1: "But like the back part goes this way, to this motor [Looked at the manual]. You see? That flipped, like the other way." Speaker 2: "No, it's this way."
Respond (RESP)	A response to a teammate that did not simply show agreement or disagreement	Speaker 1: "Do we have buttons or do we have a remote control?" Speaker 2: "Remote control."
Respond to Instructor (RtI)	Responded to instructor when the instructor asked them questions about their problems or design during their help seeking	Speaker 1: "Why does the left motor only have two and right motor have three?" Instructor: "Maybe you put a stepper motor on instead of a regular motor." Speaker 1: "Yes, we did."
Other (OTH)	Conversation not relevant to the problem being solved	"Yeah! You're the master of the programmer. I'm just a muscle. Hahaha."