Investigating Problem Solving Processes of Students, Faculty, and Practicing Engineers in Civil Engineering

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Abstract

Solving ill-structured problems is a complex task that is required of engineers who work in industry. To better prepare undergraduate engineering students for this complex task and their future professional careers, this paper provides an analysis of the results of research focusing on the study of problem-solving processes adopted by civil engineering students, faculty members, and practicing engineers. This exploratory work presents the findings of how 16 participants solved an ill-structured engineering problem and examines similarities and differences between the participants in terms of their problem solving processes. This study was guided by the following research question: What specifically are the problem solving processes of (a) students, (b) faculty, and (c) practicing engineers, and what are the similarities and differences between them when solving an ill-structured problem? In order to answer this research question, verbal protocol analysis was used. Participants were asked to think aloud as they formulated potential solutions to the proposed problem. Our findings indicated some distinct differences between students, professors, and practicing engineers in their problem-solving processes. Faculty were found to double-check their solutions and make assumptions more than students and practicing engineers, while students were found to express their feelings more and use analogies and outside knowledge less than faculty and practicing engineers. These differences between students, faculty and practicing engineers suggest that engineering curriculum and instruction should supplement

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well-structured problems with ill-structured problems in engineering classrooms to help students become familiar with multiple problem solving approaches available to them and better understand the connection between the workplace and the classroom.

Introduction

There is a growing amount of research in the engineering education field, and a notable increase in efforts to improve the engineering curriculum in recent years. Initial efforts can be seen in the early reports of the American Society for Engineering Education (ASEE) published in the 1950s. The reports of this period were focused on incorporating social sciences such as humanities and arts into sciences such as engineering and mathematics (Grayson 1977). The purpose of this integration was to focus engineering programs on solving real-world societal problems. These discussions originating in the 1950s have continued to be discussed in a variety of education-focused panel discussions, research papers, and technical reports, with an emphasis on incorporating real-world problems into engineering coursework, although some expectations have evolved since that time. Recent reports recommend that engineering students should be introduced to real-world problems as early as possible (National Academy of Engineering 2004; Phase I 2005; Olson 2013). This recommendation is also supported by engineering companies that emphasize the need for real-world practical experience (Olson 2013).

The idea of incorporating open-ended real-world problems into engineering classes has been motivated by the fact that students predominantly solve well-structured problems in the classroom, while practicing engineers solve more complex ill-structured (also called ill-defined) problems in their workplace. Because of this fundamental difference between the types of problems encountered in the classroom and the workplace and the associated problem solving skillsets needed to address them, recent studies have emphasized the importance of integrating real-world problems into engineering classes such that students are more comfortable with complex problems when they begin their professional career. Jonassen (1997) distinguished between well-structured problems and ill-structured problems in terms of instructional design requirements. According to Jonassen (1997; 2000), well-structured problems are domain-dependent, possess one single answer, and require limited application of concepts and principles. Well-structured problems are those that students and faculty usually encounter in classroom settings. Ill-structured problems, on the other hand, do not possess a prescribed solution. Their solutions are not easily predictable because they are not content-dependent and their parameters are not necessarily presented, may include conflicting information, and/or non-engineering constraints. They benefit from knowledge across multiple disciplines and are not only limited to classroom settings. These are the types of problems that are often encountered in everyday engineering practice. Jonassen (1997) makes such a distinction between well-structured and ill-structured problems, arguing that solving well-structured problems in engineering classrooms does not transfer to engineering workplace settings due to their limited context and transferability.

In light of this distinction and the emphasized gap between problem types encountered in academia and industry in the literature, a number of studies have focused on how students and practicing engineers approach complex open-ended problems (Ahmed et al., 2003: Atman et al., 2007; Chimka & Atman, 1998; Dixon & Johnson, 2011; Jonassen et al., 2006; Litzinger et al., 2010; Strobel & Pan, 2011; Swenson et al., 2014; Taraban et al., 2007). The findings of these studies indicate significant differences in terms of problem solving strategies used by engineering students and experts (practicing engineers). However, the large majority of the studies to date have focused only on students and professionals. Less work has been done to investigate the potential differences in approaches of engineering faculty in solving such problems (Atman et al. 2003). Given that it is generally engineering faculty who teach engineering students the methods and approaches to solving engineering problems, including faculty in this study to compare with students' and professionals' responses provides a new dimension to this research that we hope will provide further insights to support improving engineering education of ill-structured problem solving methods.

In summary, this study is guided by the following research question: *What specifically are the problem solving processes of (a) students, (b) faculty, and (c) practicing engineers, and what are the similarities and differences between them when solving an ill-structured problem?* This study explores problem solving processes of students, faculty, and professional engineers, in particular in the field of civil engineering. Civil engineering is chosen for several reasons. First, after military engineering, civil engineering is the oldest field of engineering which led to the formation of many engineering disciplines such as Construction Engineering, Structural Engineering, Transportation Engineering, and Geotechnical Engineering. Second, it is among the most popular engineering disciplines in terms of the number of undergraduate and graduate students in the U.S. (Roy, 2019). Rather than including the study of all engineering disciplines, given the broad nature of areas that fall within engineering, civil engineering was chosen to focus on to ensure that the sample population of participants had similar backgrounds and training. In the U.S., nearly all civil engineering programs are ABET accredited, thus choosing this discipline also provides some level of guarantee that similar types of coursework were taken by participants.

Background

Problem solving

Problem solving is one of the fundamental elements of engineering. Averill (2019) proposed a framework for students and instructors that provides the main components required to solve engineering problems, including 1. *Concepts* (i.e. fundamental theories, models, and principles), 2. *Compass* (i.e. a guide or a set of steps), 3. *Computations* (i.e. mathematical skills),

4. *Communication* (i.e. skills needed to tell a story), 5. *Consistency* (i.e. repeated use of consistent processes) 6. *Checks* (i.e. validation of solution), and 7. *Collaboration* (i.e. teamwork). Similarly, Sharp (1991) suggested that the components of the engineering problem solving model consists of identifying a need, defining the problem, collecting data, generating alternative solutions, evaluating different potential solutions, and specifying the best solution. Such problem solving models play a role in helping students improve their problem solving skills and guiding instructors in the teaching of problem solving.

There has been a growing interest in exploring how novices and experts approach engineering problems. Kolodner (1983) defines an expert as being highly knowledgeable about their domain and knowing how to use their knowledge in an effective way, while novices have no or little knowledge about a domain, are considered to have less experience, and rely on help from others (Trevelyan 2014). In order to investigate how engineers solve problems, many researchers have turned their attention to this distinction between the two groups to examine this essential aspect of engineering practice (i.e. problem solving) from a range of different perspectives.

In one approach to engineering problem solving, some researchers studied the steps completed by students in solving an engineering textbook (well-structured) problem (Kumsaikaew et al., 2006; Litzinger et al., 2010). In another approach, studies have focused on the problem-solving process, specifically solving ill-structured problems. Several researchers focused on exploring the processes used by engineering students (Atman et al., 2005; Dringenberg & Purzer, 2018; Litzinger et al., 2010), whereas others investigated how practicing engineers approach problem solving, resulting in a comparison between students and expert engineers (Ball et al., 2004; Dixon & Johnson, 2011).

However, despite the abundant comparisons of students and practicing engineers, very few studies have focused on how engineering faculty approach (ill-structured) problems (Atman et al., 2003; Holme, 2001). In one study, Atman et al. (2003) explored design strategies of four engineering faculty and compared their findings to those of a previous study on engineering students' design behavior, finding that there were some faculty whose problem solving processes were similar to those of graduating students with high quality problem solutions, some were similar to entering (freshman) students with low quality problem solutions, and, some similar to archetypal entering students. Overall, faculty's design behavior varied considerably like students' design behavior. However, these studies focused only on faculty and students without examining how professionals solve complex problems.

Given that students and faculty were found to have different approaches in terms of their processes of problem solving, and that there is very limited study on how faculty solve complex problems and the relative comparison to students and professionals, more studies are needed in this area to document the differences between engineering faculty and students, and practicing engineers. In addition, professors more commonly utilize well-structured problems when teaching engineering technical courses, as well-structured problems typically have one correct solution, and are thus more easily evaluated. As such the methods they practice and teach most commonly do not provide professors with experience and practice in improving their ill-structured problem-solving skills. Jonassen (2011) points out that worked examples and case studies are two of the components of problem-based learning environments. Worked examples are typically used in the teaching of well-structured problems to model problem solving process, while case studies are a primary form of teaching ill-structured problems that require learners to analyze existing problems and their solutions in authentic contexts and apply prior knowledge. Given that it is the engineering faculty who integrate worked examples and case studies in the engineering classrooms, their problem solving processes are worthy of further investigation. Additionally, unlike the problems practicing engineers solve on a daily basis, many engineering professors are expected to solve engineering research problems, the approach of which is significantly different than that of an ill-structured engineering problem encountered in industry. Although engineering faculty solve ill-structured problems in their workplace, the type of ill-structured problems they solve may differ in that they are generally research focused. This shows that the practicing engineers' and professors' goals and processes of solving problems are likely different but valuable in different ways, and therefore worthy of further investigation.

Verbal Protocol Analysis

One way to examine problem solving strategies is through collecting verbal protocols. Verbal protocols allow problem solvers to verbalize what they think and researchers to capture and document what a participant says. In this process participants are asked to think out loud as they solve a problem(s). Upon capturing verbalization using audio and/or video recordings, verbal protocols are typically transcribed and used to understand the problem-solving processes of participants. They can also be used for comparison of responses between different levels of participants. Verbal protocols are useful for the gathering of unfiltered data that reflect participants' complex thought processes such as hesitations, decision-making, and alternative solutions (Koro-Ljungberg et al., 2013). Since narration is less linear and not coherent, participants are less conscious about conforming to norms and expectations while verbalizing, making the generated data unprocessed. Two types of verbal protocol analysis exist: 1. Concurrent think-aloud (verbalization and decision making occur simultaneously and 2. Retrospective think-aloud (verbalization occurs after decision making) (Koro-Ljungberg et al., 2013; Kuusela & Paul, 2000).

A great number of studies have investigated how engineers solve ill-structured problems using verbal protocols (Dixon & Johnson, 2011; Douglas et al., 2012; Koro-Ljungberg et al., 2013; Taraban et al., 2007). Koro-Ljungberg et al. (2013) adopted a different approach to verbal protocol analysis. In contrast to using traditional think-aloud protocols which are typically researcher-defined processes, they focused on utilizing participant-generated knowledge through think alouds. This was done using constructivist theory combined with follow-up interviews. Their findings indicated that participant-driven think aloud methods could be used in qualitative research and aid with documentation of the complexities of the problem solving processes.

In short, a perusal of research on engineering problem solving shows that students and practicing engineers take different steps in solving problems. Within the substantial literature on engineering problem solving, an understanding of how engineering faculty solve complex problems has remained somewhat limited, because a number of studies have predominantly compared the ways students and professionals solve problems. Pertaining to these differences between students, faculty, and practicing engineers and a lack of research on how faculty approach problem solving, this exploratory study investigates the problem solving processes of engineering students, faculty, and practicing engineers to solve an ill-structured problem.

Methodology

To conduct a comparative analysis of problem-solving processes of students, faculty, and practicing engineers, in this section we summarize the utilized methods, including the participant characteristics, the development of the ill-structured problem, data collection, coding, and analysis.

Participants

A purposeful maximum variation sampling method was adopted for recruiting participants in this study (Palinkas et al., 2015). Within the scope of this study, included in this paper are the responses of seven civil engineering students, five professors, and four practicing engineers, who were recruited and asked to solve an ill-structured engineering problem. The student participants were undergraduate students (two sophomores, two juniors, and three seniors) in civil engineering at a large public university and a small public university in the Midwest region of the U.S. with no significant employment history in civil engineering as illustrated in Table 1. Of seven student participants, three of them were male and four of them were female. The faculty participants (three male, one female, and one who preferred not to answer) were also recruited from the same universities. The faculty did not have significant employment in the civil cngineering industry, with all but two having less than 5 years of experience in the industry outside of academia. The practicing engineers (three male and one female) all had over five years of experience in the civil engineering industry. Seven of the participants received their undergraduate degrees from a university classified as a large university by the Cargenie classification system ("The Carnegie classification" n.d.), five received their degrees from a medium university, and four from a small university. One of the strengths of this sample is that the participants have different level of work experience in industry and academia. In this exploratory study, we recruited both female and male students and plan to recruit more female faculty and practitioners as well as freshman students in future work.

Procedures

Problem formulation

An ill-structured civil engineering problem was developed by the research team members, including faculty members, and graduate and undergraduate students in engineering. The team generated a number of open-ended complex questions iteratively considering that the problems should be related to civil engineering and be ill-structured in nature. Jonassen's (1997) paper served as a reference in the process of ill-structured problem generation to ensure that problems followed attributes of ill-structured problems described by Jonassen. The number of generated ill-structured problems was then reduced to four and these problems were sent to the advisory board members to receive their input and guidance. The advisory board consisted of eight members, including two practicing civil engineers, two engineering faculty (one of the faculty had prior industry experience), three faculty in education with expertise in online modules, pedagogy, and problem solving, and a research scientist from psychology with expertise in data and analytics. Students, faculty, and practicing engineers all had an opportunity to review and comment on the potential problem(s) considered during the development stage of this study. Based on the board members' comments and discussions among research team members, one question is discussed in this study. The question utilized for this research is shown in Figure 1 below.

Funke (1991) categorizes the components of a complex problem as follows: 1. *Intransparency,* 2. *Having multiple goals*, 3. Complexity of the *situation*, 4. *Connectivity of variables*, 5. *Dynamic developments*, and 6. *Time-delayed effects*. The river trash problem used in this study includes many of these components. For component [2], although the major goal was to remove trash from a river, participants were asked to provide four items, i.e. they had four additional goals to accomplish, by the end of the designated time. These included an annotated drawing of their design, a plan for testing, a list of materials needed to create their proposed design, and methodology for construction of their design. In addition, they were also asked for the solution to be low cost, without impacting wildlife population and boat traffic. These represent the multiple goals [2] that were requested to be met in solving the problem. Some information was not available to the participants such as where trash was located (i.e. how deep in the river/stream), how much of the trash needed to be removed, the total budget, and flow of the stream/river, making the problem less transparent [1] and more dynamic [5]. The depth and width of the river/stream, flow rate, amount and type of trash, river channel topography, weather conditions, number of volunteers, available budget, type, size and amount of wildlife, and available tools and materials that can be used to develop a solution were some of the variables that participants had to consider for their solutions [3, 4]. Given the short amount of time participants were given to solve the problem, the last component in Funke's definition (i.e. time-delayed effects) was not considered in this study.

Data collection

All of the participants were asked to solve the selected ill-structured problem individually. Concurrent verbal protocol analysis was used to collect data during the problem solving process. First, each participant was provided with a well-defined (closed-ended) warm-up civil engineering problem, and given five minutes to solve the problem by thinking out loud, in order to familiarize themselves with the process of thinking aloud. Upon completion, participants were given the ill-structured problem, printed on a piece of paper along with several photographs to support the problem statement, and asked to solve the problem in 35 minutes. During this time, participants were asked to read and solve the problem and formulate a solution. Participants were given pieces of paper and a smart pen for recording purposes and were not allowed to use any references, including the internet. The reason participants were not allowed to use outside resources was because the focus of this research was on assessing the problem solving process within the duration offered to solve the problem, rather than assessing how participants used outside resources. The researcher in the room during problem solving acted as an observer and prompted participants to think aloud and keep talking if they fell silent during the verbalization process for more than 20 seconds. The process of problem solving was recorded. Participants were given a $20 gift card for their participation.

Data Analysis

Transcribing the collected verbal protocols was the first step for analyzing data. Each participant's audio recording was used for transcription and then timestamped. Video recordings were used as a back-up in case of any inaudible sections of the audio recording. Chi's (1997) steps in analyzing verbal protocols were followed in this study, including deciding on how to segment the protocols, developing or choosing a coding scheme or formalism, operationalizing evidence for coding (i.e. which segments correspond to the codes), depicting the mapped formalism (i.e. depicting the data graphically to present them to the audience), seeking a pattern in the depicted data, and interpreting the pattern.

One of the first steps in data analysis was to develop a codebook. For developing a coding scheme, upon reading through previous studies on engineering problem solving and selecting relevant ones, a list of codes was compiled from several studies, including Atman et al. (2005), Atman et al. (2007), Taraban et al. (2011), and Dixon and Johnson (2011). After collecting input and feedback from all team members, some of the codes were eliminated based on their relevance to the goal of this study and some new codes that emerged during coding were added to the codebook. Both emergent (i.e. codes that are different than prefigured codes) and a priori (i.e.

codes that come from the literature review) codes were used during the coding process. The final set of codes used are listed in Table 2.

The codes *problem statement*, *idea generation*, *idea expansion*, *feasibility*, connection to outside *knowledge*, and *solution selection* were used in the aforementioned four studies. We revised their definitions and names after a review of the studied transcripts. These past studies informed our research, however, we also developed our own codes such as, *double checking* and *participant emotions* based on the participants' responses. These two codes were developed by the research team after reading through transcripts, listening to audio files, and coding the pilot study transcripts. They were added to the codebook, as they occurred frequently within the transcripts. Participants expressed their emotions and double-checked their solutions and themselves several times without being prompted to do so. Given that showing emotions and double-checking are natural processes of problem solving, we decided to add these two codes to the codebook.

Upon developing a codebook, the transcribed protocols were divided into segments for coding purposes. Transcripts were coded at the sentence level, a method which has generally been followed in the literature thus far (Atman et al. 2007; Taraban et al. 2007), and which enables the coding to capture the entire problem solving process. If a sentence consisted of more than one idea, each idea was coded separately, that is, a sentence was divided into segments. Upon completion of these steps, each transcript was coded with the support of a software program, *MaxQDA*, which supports text-based coding. Codes were assigned to each sentence or phrases using the ten codes in the codebook. Five of the transcripts were coded by two coders to ensure inter-coder reliability. In case of any disagreement between the two coders, a third coder's opinion was consulted. When 80% inter-coder agreement was reached, the remaining transcripts were coded by a single coder. After coding all transcripts, the uncoded segments such as "[silence]", "[whispers]", and "[humming]" were deleted and all transcripts were merged into a single file to document the similarities and differences between the participants' responses.

The analysis of the resulting data is conducted in several ways. First the problem solving processes of each group of participants (faculty, students, and professionals) are discussed individually. Next, a comparison, including similarities and differences, across the data associated with students, faculty, and practicing engineers are made. For each group, first the number of initial ideas generated by each group of participants is discussed. One part of the problem solving process is idea generation, i.e. developing initial idea(s) of the main concept which can be further refined, and used to solve the problem. Previous research has indicated that the level of idea generation may be influenced by the level of expertise (Atman et al. 2005; 2007), as well as creativity (Ghosh 1993; Adams et al. 2009). Second is the types of final solutions that ultimately resulted from each group, which is one of the important elements of design process (Chimka & Atman 1998; Atman et al. 2007). In addition to the level of idea generation and types of final solutions, how much time was spent to solve the problem and the total number of each coded segment used by the participants (Atman et al., 2008) were examined using the same coding software program.

The resulting data were assessed as follows. First, the number of codes in each main code used by each participant was documented using the same software program, which also helped us determine how many solutions were formulated by participants. Next, the amount of time spent by each participant to solve the problem was calculated using the timestamps within the transcripts. In addition, the percentage of text coverage for each code (e.g. percentage of *idea generation* within participant transcripts) was calculated. These metrics were included in the study, as they have been commonly used in recent literature and helped to examine problem solving processes of participants. Video recordings were also used to clarify the researchers' questions and aid with the data analysis process.

Results

The findings are summarized in Table 3, 4, 5, and 6 which provide the amount of time spent to solve the problem, the number of codes for individual participants and the average across each of the three groups (students, faculty, and practicing engineers) for all participants, the percentage of the transcript associated with each code, and examples of codes from participants' transcripts, respectively.

Students

Students developed from one to five initial ideas with an average of 2.7 initial ideas throughout the 35-minute problem solving process. The portion of the text associated with the development of these ideas is approximately 5.8%. On average, student participants spent approximately 28 minutes solving the problem (Table 3), with a range of 19 to 33 minutes. The final solutions that students developed to remove trash included a range of different ideas, including a fishing net, downstream barrier, wire meshed angled wall, manual removal, mesh cage, and garbage collector device such as the use of stakes, screens, and sieves. Using a net as a component of the final solution was the most common part of a solution, either with a motor to move the net around, or for manual trash removal purposes.

The student participants were found to make a large number of idea expansion-related statements as they worked on the problem, in comparison to the other codes (Table 4). This included on average, 19.3 idea expansion codes, representing 41.5% of the text, as shown in Table 5. It was observed that in order to build on a previously stated initial idea, students mostly expanded on an idea by either developing additional details and information, making assumptions, or completing calculations. It was noted that the process of idea expansion occurred throughout their problem solving process. Upon finishing reading the problem statement, four of the student participants went about making assumptions such as "*So I am assuming these are gonna flow on the top"* (S3) and explaining why they would pick streams rather than a river to implement their solution. In addition, six students referred back to the problem while solving the problem. The problem statement code was observed mainly at the beginning of the problem solving process.

Three students also used hypothetical processes as a way to develop a solution to the given problem. For example, S6 said at the very beginning of the problem solving process "*Unless you come with a plastic solution that makes everything biodegradable once it hits water*." Similarly, S2 mentioned that "*I mean, again, if I were in this industry, I would see- look at all the previous options that have been considered and implemented to see the pros and cons of each and find the best solution from there."* These examples indicated that students relied on possible ideas or situations rather than real ones. Given that participants were not allowed to use outside resources, using such hypothetical processes is not surprising, particularly because most students did not have expertise and/or prior experience in this area. Table 6 provides more examples from participants' transcripts. Within the student transcripts, students had an average of 5.7 codes associated with discussing feasibility of a potential solution, representing an average of 12.3% of the transcripts. This was observed either by discussing workability and applicability or considering pros and cons of a solution. Discussing feasibility was usually preceded and followed by idea expansion.

As expected, selecting a solution was usually observed at the end of the problem solving process after students developed details about their solution. Without being prompted, some students explicitly stated which solution they would choose. For example, S6 said "*but that's what* *we're gonna go with 'cause that's what's in my brain."* Students also expressed their feelings during the problem solving process. This was done in three ways, including feelings about the problem, feelings about ideas/solution, and feeling about themselves as problem solvers. They made statements such as "*I hate working in my head"* (S6) to express how they felt during the problem solving, or "*Hmm, this is a cool problem and be really fun to look more detailed at the hydraulics of the water movement around the beds"* (S2) to express their feelings about the problem. Student participants mostly expressed their feelings about their ideas and solution throughout the problem solving process. Overall, statements about feelings were found in all parts of the problem solving process. Only one student (S1) did not express any feelings while solving the problem.

Connection to outside knowledge was also found within the four student transcripts, but to a lesser extent than the other two groups. This was done either using outside knowledge from the civil engineering domain or from a different domain, or using analogies, i.e. making a comparison between two situations either from a similar context (within-domain) or a different domain (between-domain). The following is an example of connection to outside knowledge within the same domain from a student (S5) transcript: "*Everything I know comes from DOT time. So, that's why- that's why I'm referring to every single time I do anything."* This student was a junior with experience working as a co-op and/or intern. In this example, the student uses their prior background knowledge that they gained through their internship at the state Department of Transportation (DOT) to solve the engineering problem. It was observed that, of four students who made a connection to outside knowledge to develop a solution, two were juniors and two were seniors and they all had a co-op and/or internship experience.

Another process that was used by students to solve the problem was double-checking. Five students double-checked either themselves, their solution, or the problem statement to ensure they covered everything in their solution or to clarify their questions as in the following example: "*To reflect. Let's go back and see if I answered everything"* (S2). This was usually observed during the middle and towards the end of the problem solving process to ensure they included all the required sections to complete solving the problem. Two students were also found to compare their ideas/solutions throughout the problem solving process as in the following example: *"So, I think-- But I'm pretty sure this will cost more than my first solution*" (S1). This student produced two solutions and discussed pros and cons of each to decide which one to implement. Although four student participants generated more than one idea, only two of them made a comparison between them.

It was observed that students who had an internship experience relied on their knowledge and experience that they had gained outside of academia to solve the problem. Hydraulics of the water movement and consulting with agencies such as US Army Corps of Engineers to get their recommendation and look at the previous solutions were heavily discussed by S2, who had prior internship experience and was a senior. This was the only student who considered education as a solution. Similarly, S5, a junior, referred to DOT while discussing what material to use. Students' experiences impacted how they approached the problem, as shown in the following example "*Um, so, my main experience is in plumbing, and so, I'm literally thinking about this as a plumbing problem*." In addition, students' showed a lack of willingness to meet the budget constraints. Although the problem required them to develop a low cost solution, students acknowledged that their solutions would be expensive, but they preferred to stick to them saying that "*but it is a solution that will last forever*" (S5) and "*this will be expensive, but it will work*" (S4).

Faculty

Overall, faculty averaged four initial ideas within their transcripts, 1.3 ideas more than students. The portion of the text associated with the development of these ideas is 7.5%, which was more than that of students. On average, the faculty participants spent approximately 22 minutes solving the problem, ranging from 15.2 to 28.2 minutes. Their final solutions consisted of using a grate and a net system, a net attached to concrete blocks, manual removal with volunteers on canoes, and a device with trash catching system. People removing trash manually was the most popular final solution among faculty, followed by using a net system, which is what students most commonly developed. It was observed that F3 developed 12 initial ideas to the given ill-structured problem, whereas the other four faculty developed between one and three initial ideas. This finding could be attributed to the participant's (F3) prior industry experience working for a civil engineering firm for eight summers.

To build on their initial ideas, faculty also expanded on these ideas with more details and information along with making assumptions and calculations. Compared to students, on average faculty had approximately two more code segments associated with idea expansion, yet idea expansion was associated with 1.6% less of the transcribed text than students (39.9%). Within the idea expansion periods, assumptions were found to be commonly used by faculty. As an example, one faculty (F1) said "*Collection in the river would be a lot more challenging, I would presume.*" Another faculty (F2) made an assumption by stating "*I just don't know like how much of the um, how much of the garbage and bags will actually flow, but let's assume that they do flow.*" It is noted that idea expansion was used in all parts of the problem solving process. During idea expansion periods, faculty were found to make a higher number of assumptions when compared to students and practicing engineers.

Although three faculty developed more than one initial idea, they did not compare their ideas explicitly, with the exception of one participant (F2). By comparison, while some students did not compare their ideas to others, similar to faculty, some students compared their ideas several times; professionals compared ideas at least once. With respect to expressing feelings during the problem solving process, faculty had a similar level of expression of emotions to students in terms of number of codes, but less percentage of text (13.2% compared to 17.8% for students). They mainly expressed their feelings about their ideas and the problem, rather than how the problem made them feel as problem solvers. For instance, one faculty (F2) expressed their feelings about ideas as follows: "*Um, …another idea would be what – but if this is a one-time thing … I mean, depending on how bad the pollution is and how much is there a collected – could this be done just like, would you have somebody going p—no I don't think that's a good solution, no*" Another faculty (F4) also made statements such as "*Oh, yeah, the backwater slews are the ones that give me the most consternation,…"*, which indicated feelings about their ideas. Expression of feelings were found within all faculty transcripts.

Connection to outside knowledge, both within and between domains, was also found within the transcripts of the faculty participants, on average similar to those of students. Using outside knowledge to solve the problem was found in three faculty transcripts (F2, F3, and F4). One example of using outside knowledge from a different domain within a faculty transcript (F4) was as follows: *"… so that means we need to find out how much of this trash comes from random… we also need to know who much is from weather. How much of this comes when the wind blows on garbage day and knocks over the garbage cans… nor do we know the rates of raccoons in the watershed. Raccoons are notorious for knocking people's garbage cans over during the wind storms*." In this example, the faculty made use of their prior outside knowledge – rates of raccoons

– to help solve the problem. In addition, faculty used analogies only to make an analogy between two situations from a similar context, as in the following example: "*So the first solution, and – and probably this will be my final solution, is to um – is the Anacostia River Navy. This is similar to the- the uh, Skunk River Navy that they have here…*" (F8).

Another process that faculty employed to solve the ill-structured problem was to double-check the problem statement and their solution. Faculty double-checked their work approximately twice as often as students. Double checking occurred after reading the problem statement (e.g., "*Anything else I'm missing in the problem statement*?"), in the middle of the problem solving process (e.g., "*What are my constraints?"* then reads from the problem statement, "*Do not affect the fish and the wildlife..."*) and at the end of the problem solving (e.g., "*Okay, is there something I'm missing like last time?").* Double-checking was found to occur in four of the faculty transcripts. It was also noted that faculty averaged 5.4 instances of problem statement codes within their transcripts, which was twice as many as students, which shows that during the allocated time period, faculty read, summarized, or paraphrased the problem statement twice as much as students.

Faculty tended to clearly define the problem and identify the cause of trash before formulating a solution. It was observed that F3 and F4 reminded themselves that the problem was a trash problem in the form of solid waste rather than a pollution problem while F2 used both terms interchangeably. F3 mentioned that "*I am gonna force myself to do 10 solutions*" and developed 10 solutions at the end of the problem solving process. This was the only faculty participant who decided to formulate a certain number of solutions at the very beginning and considered educating people as a prevention method and using drones, social media platforms such as Facebook, and games such as treasure hunt as a way of removing trash. Unlike the other four faculty, F4 focused in on actual sources of trash, such as raccoons that knock people's garbage cans over, during the first 20 minutes rather than developing a solution. In addition, F3 asked whether they could use MS excel and Matlab to solve the problem while such a request did not come from other participants.

Practicing Engineers

Practicing engineers averaged 1.5 initial ideas, which is fewer than the average number of ideas from students (2.7) and faculty (4). In addition, only 3.2% of the text of practicing engineers' is for initial idea development, which is lower than both students and faculty. The practicing engineers spent 26.5 minutes on average to solve the problem. The shortest and longest amount of time spent to work on the problem were 22.3 and 30.0 minutes, respectively. For their final solution, two of the four participants did not consider multiple solutions throughout their problem solving processes. That is, two of the practicing engineers attached to their initial idea and proposed it as their final solution rather than selecting one from a wide range of initial ideas. Practicing engineers' solutions ranged from using a grate, barriers with nets, having people use large nets, and a baffle system, thus two of the solutions included the use of a net.

With respect to idea expansion, practicing engineers had the highest amount of text (55%) dedicated to this part of the problem solving process, but a similar number of codes to the other groups as shown in Figure 2. In this portion of their problem solving process, assumptions and calculations were not as common as developing details associated with their initial ideas. In the following example, a practicing engineer (P1) builds on their inlet idea to remove trash as follows: "*Especially since there's tree branches and stuff upstream. Maybe uh, a pipe-a pipe structure that would, had to have enough, uh, it wouldn't be able to be smooth, it would have to have enough, uh, roughness to it to collect the debris*." Idea comparison was another process that two practicing engineers used when solving the problem. This part of the problem solving process averaged 2.5% of text, which is more than students (1.2%) and faculty (0.4%). For example, ideas were compared when practicing engineers debated whether to pick a river or a stream to implement a solution as in the following example "*A larger stream would- probably might cost a little bit more money just 'cause it's, it's harder to get the equipment into the river*" (P4).

Similar to students and faculty, practicing engineers expressed their feelings about the problem, their ideas, and how they felt while working on the problem. Practicing engineers mainly expressed how they felt about their ideas followed by their feelings about themselves as problem solvers and the problem statement. As an example, one of the practicing engineers (P1) said "*Yes, I'm not sure this prototype is really the best way to go."* Another practicing engineer (P2) said at the end of the problem solving process *"Um, again, I'm trying to convince myself-[chuckles] that I had a good solution."* Expression of feelings were found within all practicing engineer transcripts. Practicing engineers, however, did not express their feelings as often as students and faculty.

When making a connection to outside knowledge, practicing engineers made this connection either within the civil engineering domain or from a different domain, and did so more commonly than students areand faculty as shown in Figure 2. One practicing engineer (P2) wanted to develop a solution similar to what is being done in Baltimore, and therefore made a connection to outside knowledge from a different domain as in the following example: "*Now, I-I have seen that- And actually, it was in Baltimore harbor, have seen, they actually have small boats that just go around the harbor and all they do is collect trash in the harbor*." Similarly, another practicing engineer (P4) used their outside knowledge about a similar solution implemented in Colorado as follows: *"I have heard somebody is doing this in Colorado. They had really good results and it was cheap and they used um, aesthetics trees and they placed um, nice boulders and gravel around it. So it made it look very natural and it was like a place to come, like the park area. But it was actually just a d-- like a detention pond area that had been full of trash and other things."* Analogies were also observed within the practicing engineer transcripts which included both within-domain and between-domain analogies.

It was noted within the practicing engineer problem solving processes that the portion of the text associated with problem statement was only 2.6% compared to students (5.8%) and faculty (10.2%). This indicated that once reading the problem, practicing engineers went about solving the problem and did not go back to the problem statement to get information as often as students and faculty did. In addition, only two of the practicing engineers (P1 and P4) went back and forth between the provided problem statement and solving the problem. This showed that practicing engineers spent less time gathering information through reading the problem statement. Practicing engineers also generally double-checked either their solutions or themselves several times before they completed the problem solution. Furthermore, it was noted that the practicing engineers did not make as many feasibility-related statements as students and faculty did, which showed that they did not discuss the workability or pros and cons of their solution as much as the other two groups did. This could be because practicing engineers are more used to solving ill-structured problems in their workplace, thus know better what would work or not. Also given that they referred to similar solutions implemented earlier in other places, they might have assumed which solution would be feasible or not without saying it out loud.

Practicing engineers heavily relied on their prior work experiences to solve the problem and involved stakeholders such as users and residents in their problem solving. Personal experiences and classes that they have taken also played a role in practicing engineers' problem solving processes. P3 mentioned their experience living close to the water and seeing trash in rivers before and a field trip to a polluted area in a Hydrology class that helped them see a few solutions such as barriers, stating "*Um, the more I'm thinking about my water classes, obviously, we'd wanna locate it on the inside of the corners*." It was observed that P3 also approached the problem from the perspective of a resident living in that location. They stated what they would feel as a member of that population, if the proposed solution were implemented. Likewise, P2 recounted the times when as a kid how they tried to get minerals from streams for fishing using a small net and their trip to the Baltimore harbor where they saw small boats that collect trash. These childhood memories, personal and professional experiences and observations, and field trips as part of courses affected their development of a solution.

Discussion

Our research question examines problem solving processes of students, faculty, and practicing engineers when solving an ill-structured engineering problem. A closer look into student, faculty, and practicing engineer transcripts revealed both similarities and differences across the three groups. Using a net system or grate followed by downstream barrier and manual removal were popular solutions across students, faculty, and practicing engineers. Another similarity was that all the participant groups offered, on average, more than one initial idea to the given ill-structured problem, with slightly higher numbers with faculty and students. In addition, they all made use of expanding idea details, assumptions, and calculations to detail their initial solutions. In order to see if their solution was feasible, they questioned the workability and applicability of their idea and discussed its advantages and disadvantages. While doing so, it was observed that they expressed their feelings about the problem, themselves, and their solutions. It was also noted that the participants used their prior knowledge (i.e. made a connection to outside knowledge) and double-checked their solutions during the problem solving process. In summary, most codes were used, on average, by all three groups. This suggests that we are inherently aware of the processes adopted by engineering students, faculty, and practicing engineers when solving an ill-structured problem. However, given that the order and frequency of these codes along with how much time is spent on the task overall and in each process of problem solving differed across participant groups, these may have implications on the quality of the problem solution.

In this study, we found that the students spent slightly more time overall solving the problem (i.e. developing a solution and responding to the four items requested in the problem statement within the allocated time) than the faculty and practicing engineers, although the difference is small. This differs from the findings of Atman et al. (2007) who found that industry professionals spent more time solving the problem overall than the students. One explanation for this may be the type, difficulty, and complexity of the ill-structured problem in this study and the associated amount of time the students spent understanding the problem. In the study by Atman et al. (2007), participants were given up to three hours to complete the task, while in our study participants were given 35 minutes. In addition, Atman et al. (2007) stated that their ill-structured engineering problem was a general topic, that is, it was not in the participants' area of domain. In this sense, since the problem in this work is civil engineering specific, this may have influenced the familiarity of the professionals to the problem as compared to students, and thus the differential time taken to solve the problem. All these factors could influence the amount of time spent solving the problem.

In addition, we found that the text coverage for the problem statement code within the student transcripts, which was used to understand the problem, was more than twice as much as those of practicing engineers. This finding is in agreement with Dixon and Johnson's (2011) finding which indicated that students spent more time in the problem identification stage than professional engineers, while experts only spent a limited amount of time identifying the problem. In addition, we found that the faculty spent the shortest amount of time overall solving the problem and the percentage of text for the problem statement code was highest within the faculty transcript. Similar to Atman et al. (2003) who found significantly different amounts of time spent by four faculty solving the problem, we found that among the three participant groups, faculty had the highest variation in terms of time spent to solve the problem. Thus, the length of time given to participants to solve the problem, type of problem, and prior experience with ill-structured problems may have impacted how much time participants spent overall solving the problem.

A similarity among the studied groups occurred for *idea expansion*, which dominated the design processes of students, faculty, and practicing engineers. This was followed by feasibility analysis and participant emotions. These findings support the results of Atman et al. (2005; 2007), which suggested that practicing engineers and students spent most of their time expanding an idea in the problem solving process. We also note however, that, interestingly, the amount of transcribed text associated with each of these portions of the process is most similar, between faculty and students, rather than faculty and professionals. These resembling design processes between students and faculty raise educational questions and implications and suggest further research opportunities. Perhaps these similarities suggest that students mostly learn their problem solving skills from their professors who teach problem solving in academic settings and, for that reason, the problem solving processes of students differ from those of practicing engineers. Given this, students' problem solving processes resembling those of faculty is not surprising, unless they are exposed to opportunities such as internships/co-ops outside of academia during their undergraduate studies. Our results related to *connection to outside knowledge* showed that junior and senior students who had an internship experience used more prior knowledge and drew more analogies similar to practicing engineers. Perhaps some engineering design courses can benefit from being taught or co-taught by practicing engineers with a significant amount of industry experience (as real-world engineering design projects are prime examples of ill-structured problems) to implement learning practices in engineering classrooms that help students get familiar with practicing engineer-like problem solving processes. This is already practiced at some institutions for design and capstone type courses.

One of the differences across students, faculty, and practicing engineers when solving an ill-structured problem was the use of assumptions by faculty as they expanded on an initial idea, i.e. faculty used more assumptions than the other groups. This may be attributed to the nature of research-intensive faculty positions' activities that do not usually involve solving ill-structured problems similar to those in industry on a daily basis when teaching engineering courses, or conducting research. Research related tasks also require making assumptions, but can also be driven by the need to challenge and test engineering assumptions commonly made in engineering practice to further the state of the art. Similarly, faculty was the group that double-checked their solutions most when compared to students and practicing engineers. This also could be because of the aforementioned reasons, or that research in general requires the checking of solutions over a longer period of time prior to, for example, publication, whereas an industry-related problem is often solved on a quicker timeline where there is less time for consideration of detailed double checking. Another potential explanation for this difference in the frequency of double checking and assumptions might be participants' self-efficacy. Carberry et al. (2010) categorized engineers with firsthand engineering experience as high self-efficacy group and undergraduate engineering students as intermediate self-efficacy group after surveying a large number of participants. This suggests that self-efficacy may play a role in participants' making assumptions and double-checking.

The literature suggests that while solving a problem, most practicing engineers typically attach to a single early solution and make modifications to that idea rather than formulating a wide range of alternative solutions (Cross, 2004). What we encountered in our findings was the average number of alternative solutions the practicing engineers produced was 1.5. Two of the practicing engineers developed two alternative solutions, while the other two only developed one solution. Upon a detailed review of the transcripts of the two practicing engineers who formulated two alternative solutions, we found that in one of the transcripts, one of the alternative solutions developed was a prevention method (i.e. catching pollution as early in the process as possible) rather than a concrete solution such as a net system. Thus, overall our findings indicated that practicing engineers attached to a single idea throughout their problem solving process, resonating with Cross' (2004) findings. The students and the faculty, in contrast, averaged 2.7 and 4 alternative solutions, respectively. While the practicing engineers gave examples of preimplemented solutions from other parts of the country as they worked on the task and integrated them into their problem solving processes, it was observed that the students and the faculty initially pursued alternative strategies without attempting to develop a similar pre-existing solution and adapting it to the context of the problem. As stated by Atman et al. (2007), these observations indicate that students and particularly faculty may have a more limited repertoire of previously solved ill-structured problems and thus generate multiple solutions compared to practicing engineers who tend to formulate a more promising solution initially and make it work for the rest of the problem solving process. Another explanation for practicing engineers' developing fewer number of alternative solutions may be that they are used to working for for-profit companies which operate in a time sensitive work environment on a daily basis. Given the time constraints, they may have applied these habits to their problem solving process in this study.

An analysis of students' and practicing engineers' use of outside knowledge showed that differences existed in the types of analogies employed. Our findings indicated that students tended to use more between-domain analogies (i.e. they drew analogies between two ideas from different domains), while practicing engineers used more within-domain analogies (i.e. analogies from the same domain), which contradicted the findings of Dixon and Johnson (2011) who found that engineering students used more within-domain analogies and practicing engineers used more between-domain analogies. More broadly, however, the practicing engineers surpassed the students and faculty in the percentage of connection to outside knowledge used drawing more analogies and referring to outside knowledge. Practicing engineers' use of connection to outside knowledge shows that they have a better grasp on similar types of ill-structured problems and what type of solutions have been developed to solve such problems in other parts of the country, which helped them formulate their solutions.

Unlike the faculty and practicing engineers, the students did not make connections to outside knowledge as much as faculty and practicing engineers. This could be because students are not as experienced as faculty and practicing engineers in terms of solving ill-structured problems. When students' year of academic study was examined, it was found that two of the students who were sophomores did not make use of any outside knowledge or draw analogies, while junior and senior students employed these processes, although it was not as much as faculty and practicing engineers. It was observed that the junior and senior students who made a connection to outside knowledge all had a co-op and/or internship experience. Therefore, such observations suggest that students make a connection to outside knowledge as they gain more experience, particularly through industry experience. This finding could also be attributed to students' making more hypotheses and proposing solutions that seemed possible rather than actual. One implication is that exposing students to workspace problems starting from their freshman year in engineering classrooms or providing them with internship opportunities early on in their engineering careers to gain experience in the engineering industry could help students to familiarize themselves with ill-structured problems and better prepare them for their future professional career.

An additional finding with regard to students was that they expressed how they felt about the problem and the problem solving process more often than the faculty and practicing engineers without being prompted to do so. This was found in statements such as *"I am not qualified for this"* and *"I'm thinking a way too uh, primitive with what I'm thinking right here"*, which were found less within the faculty and practicing engineer transcripts. One explanation for this is that students are not familiar with solving ill-structured problems as much as practicing engineers and faculty, thus they may express how they feel about it as they are working on the problem. Research shows students think that they are not exposed to ill-structured problems in their classes as much as well-structured problems and feel uncomfortable solving them due to problems' ambiguous nature (McNeill et al., 2016) and that they find ill-structured problems more challenging than classroom problems (Pan & Strobel, 2013). Perhaps due to these challenges that students think they face when solving an ill-structured problem, the student participants in our study expressed their feelings out loud more than faculty and practicing engineers.

Conclusions, Recommendations, and Future Work

From our findings, we have a better understanding of the problem solving processes of undergraduate engineering students, faculty, and practicing engineers take when solving an ill-structured problem. This paper presented a comparative analysis of problem solving processes of engineering students, faculty, and practicing engineers and highlighted a number of similarities and differences in how students, academic professors, and professional engineers approach an ill-structured problem. This study also adds to the literature on engineering education by examining faculty in addition to students, and practicing engineers. The results demonstrated that the problem solving processes were variable across participant groups and none of the participant groups adopted a single strategy.

This study provides the following unique contributions:

- New codes such as "participant emotions" and "double checking" were added to the codebook and the existing ones in the literature were re-defined to document problem solving processes of participants. Overall, a more comprehensive codebook was developed.
- We examined problem solving processes of engineering faculty in addition to those of students and practitioners. This helped us explore how these three groups solve an ill-structured problem and identify similarities and differences across them.

- Our findings indicated variation in terms of problem solving processes of students, faculty, and practitioners and that there is not a standard method to solving an ill-structured problem.

The main implications of the study are summarized below.

- The variability of problem solving processes across participants indicates the complexity of the design process used for solving ill-structured problems. We suggest integrating real world ill-structured problems in engineering classes to help students familiarize themselves with different methods to these problems. More cooperation between faculty and practitioners through workshops, technical conferences, and meetings, as well as through working on collaborative projects may help both faculty and practitioners familiarize themselves with multiple approaches and transfer this knowledge to their students.
- We recommend creating more internship, co-op, and other work opportunities for engineering students as early as possible to expose them to real-world problems and help them develop ill-structured problem solving skillsets in addition to the skills that they gain in the engineering classroom. These experiences outside of academia could also help students feel more comfortable and confident during problem solving given the observed negative feelings about the problem and themselves that they expressed while solving the problem.
- Resembling design processes between students and faculty suggest that students learn their problem solving skills from their professors. We suggest practicing engineers be involved in (co)teaching of design courses to aid students with getting familiar with practitioner-like problem solving behavior. In this way, students can be exposed to a variety of ill-structured problem solving processes of both faculty and practitioners as part of their development rather than following a step-by-step guide. Faculty with industry experience can also help to contribute to the teaching of ill-structured problem solving processes.

The findings of this study indicated that the problem solving processes of students, faculty, and practicing engineers are not monolithic. These findings can raise awareness of the similarities and differences between engineering students, faculty, and practicing engineers in their problem solving processes, which can lead to more conscious planning of teaching of ill-structured problem solving methods. The findings of this study provide a foundation for future studies examining problem solving processes adopted by engineers.

The results and limitations of this study suggest several avenues for further research. First, we worked to investigate the problem solving processes of engineering students, faculty, and practicing engineers when working on an ill-structured problem within the domain of civil engineering. The major focus of this study was to examine the design processes of participants, therefore evaluation of solution quality was not taken into account. However, further studies are needed to fully examine problem solving processes including other aspects such as design and solution quality using a larger data set. This work did not include factors such as race, gender, age that can also influence problem solving, which may impact transferability of our findings to other settings. Thus, future research is recommended to recruit more female participants and participants from a racially and ethnically diverse background to better understand problem solving processes used by engineers and apply our findings to other contexts.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. These include the codebook and coded transcripts.

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Table 1. Characteristics of participants

Role	**Year in school**	**Gender**	**Ethnicity**	**Work experience in industry**	**Work experience in academia**	**# of design courses taken**
Student	sophomore	female	Asian/PI	none	none	not reported
	sophomore	male	white	none	none	1-2
	junior	female	white	1+ sem. intern	none	1-2
	junior	female	white	1+ sem. intern	none	1-2
	senior	male	white	1+ sem. intern	none	3-4
	senior	female	white	none	none	not reported
	senior	male	white	1+ sem. intern	none	1-2
Faculty	NA	male	white	none	+5 years FT faculty in CE	+5
	NA	female	white	none	none	1-2
	NA	male	white	8 summers CE firm	none	1-2
	NA	prefer not to answer	white	1+ sem. intern; +5 years FT in CE	< 5 years FT faculty in CE	+5
	NA	male	white	1+ sem. intern;	< 5 years FT faculty in CE; 1+ sem. TA/RA	+5
Practi-cing engineer	NA	male	white	+5 years FT in CE	none	3-4
	NA	male	white	+5 years FT in CE	none	3-4
	NA	male	prefer not to answer	+1 sem. intern; +5 years FT in CE	+1 sem. TA/RA	+5
	NA	female	white	+1 sem. intern; +5 years FT in CE	+1 sem. TA/RA	1-2

Note: CE = Civil Engineering, FT = full-time*,* NA = not applicable, PI = Pacific Islander, RA = research assistant, sem. = semesters, TA = teaching assistant.

Table 2. Coding scheme used to compare problem solving processes of participants

Codes	Definitions
Problem statement	Read the problem statement, paraphrase, summarize, interpret, or repeat verbatim
Idea Generation	Generate a new idea (i.e. potential solution to the problem), but only includes minimal details; this idea must be new and not previously stated
Idea Expansion	Develop a previously stated initial idea into a detailed idea, such as through numerical calculations and making assumptions to support idea expansion
Hypothetical Process	Discussion of a hypothetical methodology to follow to solve the problem
Feasibility	Discussion of if the detailed idea is likely to work, is doable, and/or is applicable
Idea Comparison	Compare one idea to another idea
Participant Emotions	What participants feel about the problem, themselves and their ideas/solution
Connection to outside knowledge	Reference to outside knowledge (i.e., past experience)
Double checking	Double check their understanding of the problem statement, their ideas, and/or their solution
Solution Selection	Summarize the final solution, indicate what idea to choose as final solution

Table 3. Time spent to solve the problem

Student	**Time (min)**	**Faculty**	**Time (min)**	**Practicing engineer**	**Time (min)**
S1	19:21	F1	21:49	P1	22:29
S2	29:32	F2	15:18	P2	25:08
S3	33:09	F3	21:34	P3	30:00
S4	27:08	F4	28:26	P4	29:48
S5	29:10	F5	23:19		
S6	29:36				
S7	29:43				
Average time	**28:14**		**22:05**		**26:51**

Note: S = student, F = faculty, P = practicing engineer.

Table 4. Number of codes used by participants

Participant role	Participant #	Problem statement	Idea generation	Idea expansion	Hypothetical process	Feasibility	Idea comparison	Solution selection	Participant emotions	Connection to outside knowledge	Double checking
Students	1	2	2	3	0	1	1	2	0	0	0
	2	4	2	18	1	9	3	3	13	3	4
	3	1	3	11	0	2	0	1	1	0	0
	4	6	5	20	0	14	0	0	5	4	2
	5	4	1	28	3	7	0	2	9	4	1
	6	2	1	20	1	4	0	3	10	0	5
	7	0	5	35	0	3	0	1	20	2	7
	Average	**2.7**	**2.7**	**19.3**	**0.7**	**5.7**	**0.6**	**1.7**	**8.3**	**1.9**	**2.7**
Faculty	8	1	3	15	0	1	0	0	2	0	0
	9	4	2	25	0	8	1	3	11	1	4
	10	7	12	19	0	7	0	1	13	4	14
	11	11	2	15	0	9	0	0	8	7	1
	12	4	1	32	2	9	0	0	1	0	6
	Average	**5.4**	**4.0**	**21.2**	**0.4**	**6.8**	**0.2**	**0.8**	**7.0**	**2.4**	**5.0**
Practicing Engineers	13	1	1	20	0	4	0	0	3	0	0
	14	0	2	9	1	5	3	0	5	3	0
	15	4	1	45	0	1	0	2	14	8	8
	16	0	2	29	1	5	1	0	1	2	5
	Average	**1.3**	**1.5**	**25.8**	**0.5**	**3.8**	**1.0**	**0.5**	**5.8**	**3.3**	**3.3**
Overall Average		**3.2**	**2.8**	**21.5**	**0.6**	**5.6**	**0.6**	**1.1**	**7.3**	**2.4**	**3.6**

Table 5. Percentage of codes and standard deviation across participant transcripts

Codes	Student transcript (n = 7) (%)	Student transcript SD	Faculty transcript (n = 5) (%)	Faculty transcript SD	Practicing engineer transcript (n = 4) (%)	Practicing engineer transcript SD
Problem statement	5.8	5.3	10.2	6.3	2.6	2.4
Idea Generation	5.8	6.2	7.5	6.5	3.2	2.3
Idea Expansion	41.5	11.4	39.9	18.9	55.0	17.1
Hypothetical Process	1.5	1.9	0.8	1.6	1.1	1.7
Feasibility	12.3	6.7	12.8	5.1	7.9	6.7
Idea Comparison	1.2	3.4	0.4	0.7	2.1	4.7
Participant Emotions	17.8	9.9	13.2	6.7	12.2	6.8
Connection to outside knowledge	4.0	3.2	4.5	5.5	6.9	4.7
Double checking	6.2	4.7	9.4	7.3	7.9	6.5
Solution Selection	3.7	5.4	1.5	2.1	1.1	1.2

Note: SD = standard deviation.

Table 6. Examples of codes from participants' transcripts

Problem Statement

- Okay. So, we're trying to remove trash from our river system and there are plastic-- mostly plastic, and pretty much all plastic, it seems, and paper. Um, and then, all small-- pretty small things like food wrappers, bottles, and cans, nothing massive. – *F5*
- … because, in the requirement it says, the solution should not hinder any boat-- boat traffic,… - *S5*

Idea generation

- Um, one option for the main river might be to, um, yeah, need something like this maybe with um, some logs" – *P4*
- So I would first of all, examine available options and presumably a lot of these would include different types of grates or nets or some types filtration devices. - *F4*

Idea Expansion

- One, two, three, four, five, six, seven, eight, okay, nine, ten. So, make an assumption, say that probably 10 mainstreams contributing to the-to the river. – *S2 (making an assumption)*
- Okay. What I'm showing now is this process within the narrow streams to just having again, something like a- Like a large net but is fairly lightweight. But well, you can just- You could walk upstream, have a person on each side and maybe people walk-walking along this side, making sure that anything's caught in grass, whatever could be thrown into the net or pulled out… - *P2 (expanding idea details)*
- And then we are- what's the remaining percentage- and 25 plus, let's see that's 51, 73, and 70. No. Let's get a calculator out. Only 27% risk… - *F4 (making calculations)*

Hypothetical process

- You could add sensors onto them, that like- -can turn into how much weight is like being, w-what the tension is in our carabiner, and if it's more than a certain amount, that when it's time to clean it, but that might cost you much to do. And seems a little bit overkill, but in a perfect world, we would do that. – *S5*

Feasibility

- You can make an outlet for, to go to the, to let the water go back out of these collection pits, so you can then put a screen over the inside, the problem is that, that's going to clogged up right away and then it's not going to be effective anyway. So that's not going to be functional. – *P1 (discussing both pros and cons and workability of their solution)*
- There's never a cheap fix. It's what my dad always says, "There's never a cheap fix." This will be expensive, however, it will work. – *S4*

Idea comparison

- if you don't change people's mindsets of throwing things in the river then you know it'll just keeping a problem. So again that would be- that would be a more ideal sustainable solution is education. – *S2*

Participant emotions

- You can tell I'm getting tired. – *P2 (expressing how they felt about themselves)*
- Okay, so, this is a little unclear – *F2 (while reading the problem statement)*
- So I don't like the dragline option even though it's the first one that came with me, uh, came to me.– *P3 (expressing feelings about their ideas)*

Connection to outside knowledge

- Um, so, my main experience is in plumbing, and so, I'm literally thinking about this as a plumbing problem. – *S4 (between-domain analogy)*

- … we went on a field trip, you've looked at a couple of things I remember in Hydra one. Two caps down, you know. Um, you're gonna get the picture first on this one. - *P3 (connection to outside knowledge - within -domain)*
- Geez. Mm-hmm. That's probably about right. So, you'll want, for sure, like a 12-inch diameter tile. I don't know, let's just say- So, there are 100 yards on the football field, which is 300 feet. So, if I say 500, so I'll say 1000. – *S4 (connection to outside knowledge - between -domain)*

Double checking

- All right. Hmm, we have the drawing, we have the materials. We have the methodology. What are we missing? What are we missing? – *S6 (double-checking themselves)*
- It doesn't say anything in here. Um, it doesn't say anything about here about any kind of, um, bird or fowl life. – *P3 (double-checking problem statement)*

Solution selection

- Yep, that's what we're gonna do, okay. – *S6*
- I think that's the way to go. - *S2*