A Qualitative Analysis of How a Student, Faculty, and Practicing Engineer Approach an Ill-structured Engineering Problem

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Abstract

Solving open-ended complex problems is an essential skill for part of being an engineer and a common activity in the one of the qualities needed in an engineering workplace. In order to help undergraduate engineering students develop such qualities and better prepare them for their future careers, this study is a preliminary effort to explore the problem solving approaches adopted by a student, faculty, and practicing engineer in civil engineering. As part of an ongoing NSF-funded study, this paper qualitatively investigates how three participants solve the following research question: What are the similarities and differences between a student, faculty, and practicing engineer in the approach to solve an ill-structured engineering problem? Verbal protocol analysis was used to answer this research question. Participants were asked to verbalize their response while they worked on the proposed problem. This paper includes a detailed analysis of the observed problem-solving processes of the participants. Our preliminary findings indicate some distinct differences between the student, professor, and practicing engineer in their problem-solving approaches. The student and practicing engineer used their prior knowledge to develop a solution, while the faculty did not make any connection to outside knowledge. It was also observed that the faculty and practicing engineer spent a great deal of time on feasibility and safety issues, whereas the student spent more time detailing the tool that would be used as their solution. Through additional data collection and analysis, we will better understand the similarities and differences between students, professionals, and faculty in terms of how they approach an ill-structured problem. This study will provide insights that will lead to the development of ways to better prepare engineering students to solve complex problems.

1. Introduction and Background

Problem solving has been identified as a 21st century skill [1], [2] and an essential part in the education of all engineers. In the report by the Secretary's Commission on Achieving Necessary Skills (SCANS) [3], solving problems is considered one of the essential skills and personal qualities needed in a workplace. The report identifies a high performance workplace as a problem-oriented environment and suggests that students should be taught solving complex problems along with other basic skills such as reading, writing, and speaking, rather than in isolation. Similarly, the Accreditation Board for Engineering and Technology (ABET) [4] states that problem solving in engineering should address complex problems and that engineering faculty should understand problem solving. Given that problem solving is an expected skill of engineering students, faculty, and practicing engineers, it should also be essential to education in addition to the workplace.

Jonassen [5] defines ill-structured problems as emergent dilemmas because they are part of our everyday lives. They are not limited to classroom contexts, require integration of various fields, and have unknown elements unlike the majority of problems students are given in engineering classrooms. Several studies have examined how students solve ill-structured engineering problems [6], [7], [8], [9], [10], [11], [12], including how engineering students perceive workplace problem solving [13], [14], the similarities and differences between students and expert practitioners [15], [16], [17], the problem solving processes of practicing engineers [18], [19], and design processes of engineering faculty [20]. The results of these studies indicate differences between students and practicing engineers. Leppävirta et al. [10], for instance, found that solving complex problems improved students' skills needed to carry out procedures when working on a problem and increased students' motivation to learn. With respect to differences between students and practicing engineers, Atman et al. [16] found that practicing engineers spent more time solving the problem than the students did, particularly in the process of gathering information and problem definition. In another study, Kothiyal et al. [11] found that when given delayed guidance (i.e. unguided student exploration of an ill-structured problem followed by problem solving instruction), students developed complex problem solving skills and showed a wider range of problem solving behavior. In addition, Atman et al. [20] examined four faculty's problem solving approaches and found that gathering information and generating ideas were the two commonly used steps adopted by faculty and their design behavior varied considerably. Previous studies also indicated differences between freshmen and seniors in terms of their design behavior. For example, Atman et al. [7] found that although both freshmen and seniors allocated time amongst their design steps similarly, seniors developed higher quality solutions and showed a more sophisticated design behavior.

Drawing from a larger ongoing NSF-funded study on exploring how 50 students, 25 faculty, and 25 practicing engineers in civil engineering approach open-ended complex problems, this qualitative paper focuses on an in-depth analysis of how an engineering undergraduate student, faculty, and practicing engineer solve an ill-structured problem. Focusing on one participant from each group of participants allows for a more detailed understanding and examination of how the participants solve an engineering problem and provides insight into the following research question, which guided this study: *What are the similarities and differences between an engineering student, faculty, and practicing engineer in the approach to solve an ill-structured problem?* Given the similarities and differences between engineering students, faculty, and practicing engineers in the literature, this paper, as a preliminary step to a much larger study which aims to include a total of 100 participants, encompasses all three groups of participants, namely a student, faculty, and practicing engineer. The goal of this research is to explore the steps that the participants take when solving an ill-structured engineering problem and investigate their problem solving behavior. This includes assessing how much time they spend working on the problem, whether they ask any questions or seek assistance during the problem solving process, whether they generate multiple alternative solutions, and how design processes of a student compare to those of a faculty member and a practicing engineer. Examining such differences in the problem solving processes of participants will help to understand the differences between academic preparation in solving ill-structured problems and problem solving approaches used by practicing engineers. It will also help to guide development of course materials that may be used in the engineering classroom.

II. Methods

Participants

Three participants were selected from a larger dataset as part of an ongoing research project. Since the goal was to examine the similarities and differences between students, faculty, and practicing engineers, one participant from each group was randomly chosen to document how they formulated a solution to an ill-structured engineering problem and what each participant did during each of the steps of problem solving. The student participant was a female junior student in civil engineering studying at a small university located in the Midwest. The student participated in a co-op or intern in a technical position across multiple semesters. The faculty was a male associate professor in civil engineering at a large university in the Midwest, with more than five years full-time employment at a higher education institution. The practicing engineer was female with Master of Science and Associate of Science degrees. The engineer graduated from a small size Masters-level university, and worked one or more semesters as an intern and a graduate research assistant. The engineer had more than five years full-time employment in civil engineering industry, as shown in Table 1. All the participants took part in the study voluntarily and were given $20 for their participation.

Table 1. *Profile of participants*

Participant	**number of undergraduate design courses taken in CE**	**size of institution attended as an undergraduate**	**area of specialization**	**industry work experience**
Student	1-2	small	structural	none
Faculty	5 or more	medium	transportation	none
Practicing engineer	1-2	small	water resources	5+ years

Note: CE =Civil Engineering

Data Collection

A verbal protocol analysis (VPA) was implemented in the study to collect data. This is a method used to elicit cognitive processes of problem solvers as they work on a problem. Problem solvers are prompted to think aloud and verbalize their thoughts while working on a task. VPA has been commonly used in the literature to understand engineering students', professors', and practicing engineers' problem solving behavior [6], [7], [8], [9], [15], [16], [17], [21].

In order to help participants with the think-aloud process, each was given a warm-up problem first, which took five minutes, to help them to familiarize themselves with the think-aloud process. Upon completion of this warm-up problem, they were given the ill-structured problem along with pieces of blank paper and a smart pen that had a camera and microphone. This helped the research team document what participants were writing and thinking aloud at the same time. The text of the ill-structured problem is included in Figure 1. This ill-structured problem was developed by research team members, along with other problems, and sent to the project advisory board members for feedback. Participants were asked to read the problem first and then formulate a solution in 30 minutes. They were instructed to think aloud while they worked on the problem. When they fell silent for more than 20 seconds, an interviewer reminded them to think aloud. The participants were not allowed to use the Internet during the problem solving process. Problem solving processes of participants were audio and video recorded for transcription purposes. Each participant also filled out a demographics survey.

Gum Removal in Central Park

Removal of gum from city streets and sidewalks cost cities in the U.S. hundreds of millions of dollars each year. Given tight budgets that cities are facing currently, they are looking for new solutions to this ongoing problem of gum that is discarded and becomes stuck to the city's paved surfaces, creating unsightly pathways. You are an engineering consultant, who has been hired by the city of New York (NYC)'s Parks Division to assess the problem and develop a solution that removes the large majority of gum on a variety of places in the park (e.g., on walk pathways, stairs, sign posts, benches, and trash bins). They are specifically targeting the Bethesda Walkway of the Central Park area of NYC (see diagram below, approximately 1.5 miles long by 0.5 miles wide), which they prioritize for keeping the cleanest among all parks in NYC as it is a national historic landmark. Please keep the following in mind and address each of these in your answer:

- The city budgets approximately 4.5 million per year to maintain Central Park. However, only a small fraction of this budget goes to gum removal, your solution should be mindful of a low budget.
- The park is open to visitors 365 days a year from 6 am to 1 am. Many people utilize the park, particularly during the daylight hours. The *Park Director of Operations* does not want any major interruption to typical use of the park for cleaning purposes during daylight hours, including all modes of transportation (e.g., walking, running, biking riding, and skateboarding). However, the *Park Safety Office* has also warned that people do use the park at night, particularly now that security in and around the park has improved, and he does not want to have to deal with increased safety related issues due to the proposed solution implementation at night. Additionally, the entire width of a sidewalk cannot be closed off at one point. Safety, public access and aesthetic priorities should be balanced in the solution.
- The *Director of Landscaping* for the park has told you that it is very important to preserve the trees, bushes, plants and water body health as these are the reasons that people come to central park. She strongly encourages you to develop a solution that does not significantly negatively impact the environment (e.g., water, air, soil) or the animals or people using the park.
- *The Director of Maintenance* has indicated that the parks' sidewalks must support 3/4-ton maintenance and service vehicle trucks. The structural integrity of the sidewalks and roads should not be compromised over time, as the city only has budget to replace sidewalks every 20+ years.
- There are certain locations that have very high volumes of traffic and others that are less heavy. There are also certain areas that have more concentrations of gum than others. These are highlighted with stars on the map. Select one of the areas that you would choose to test your solution on.

You are tasked with the development of **an initial design of a solution** to this challenge, including:

A) An annotated drawing and description of the design that will be used for achieving gum removal

B) A plan for testing this method in select locations to prove it works in all anticipated conditions
C) An operations procedure and schedule to be followed to implement this solution twice a year
D) A list of materials needed.
E) Methodology for construction.

Figure 1. Ill-structured problem used for the study

Data Analysis

Verbal protocols (i.e. recordings of participants verbalizing) were transcribed for data analysis. Each transcript was coded independently by two coders using a software program, MaxQDA. Coders met to discuss coding until reaching a consensus and when the two coders had a question or disagreement, a third coder's guidance was sought. 80% agreement between coders was achieved. Coding was done following a codebook that was both compiled from the literature and developed by the research team, as shown in Table 2. While some of the codes were taken from previous studies [6], [7], [8], [16], [21], new codes were also added to the codebook, or modified versions of previous studies. This was an iterative process that took the research group several months to refine. Coders met twice or three times each week throughout one semester to develop the codebook and complete the pilot coding.

After each transcript was coded, all the uncoded, blank portions such as "[silence]" and "[unintelligible]" were deleted, then all transcripts were merged into a single document for comparison purposes. Steps taken by the participants to solve the ill-structured problem are discussed in the results section. Data presented below does not include the time when participants were instructed to read the problem. Individual participants will be referred to as "they" throughout the paper as recommended by American Psychological Association (APA) [22].

Table 2. *Codes for gum removal problem*

Design step	
Problem statement	Read, understand, and interpret the problem
Idea generation	Develop ideas for a solution
Idea expansion	Explain how to develop an idea, provide details such as dimensions and material type
Hypothetical process	Describe a hypothetical methodology that can be used to solve the problem
Double-checking	Make sure the problem covers all the requirements
Feasibility	Determine applicability and pros and cons of a potential solution/idea
Idea comparison	Compare alternative ideas
Solution selection	Select which solution to use among alternatives
Participant emotions	Express feelings about the problem, solution and themselves
Connection to outside knowledge	Use prior knowledge and make analogies

III. Results

Analysis of Student

The student participant spent 30 minutes solving the problem, using all the allocated time. They did not ask any clarification questions during the problem solving process. Although they were given time to read the problem before the timer was started, they went about solving the problem by reading the instructions again. Before developing an initial idea, they discussed what time was available to implement their potential solution, and whether that time frame would be feasible for implementation. Then they introduced scraping the gum off using various sized scrapers as their solution to the gum problem.

What was noticeable within the student's problem solving process was that during the *idea generation* and *idea expansion* steps, they discussed how to remove gum from sidewalks, benches, signs, trash cans, and stairs separately and developed a solution accordingly by considering factors such as what type of material the benches were made out of, and the size and type of paths the sidewalks followed. The student spent a great deal of time designing the scrapers, how large they should be, and what material they would be made out of.

While working on the problem, they also expressed their feelings about the gum problem, stating "*Why aren't they in trash bins? That's so stupid. People suck*", and about themselves when they made a spelling error while writing "*That's not how you spell features, I am an engineer, I need to know how to spell, oh, that needs a capital.*" They also expressed uncertainty about the cost of the solution "*…all in all, it's gonna be for materials, and then labor to put them together, so I don't know how much the stuff costs, I'm not gonna guess more than $5,000 to create these things, probably less than that honestly*" and dimensions of the scraper. All the design steps listed in Table 2 were used by the student participant, although some were used more frequently than others such as *idea expansion* and *participant feelings*. The *double checking* and *problem statement* steps occurred at the beginning of the problem solving process, while *solution selection* occurred at the end. Prior knowledge about the size and type of the sidewalks was also implemented by the student. To implement their solution they picked a location which was isolated from main roads and paths to reduce any potential negative impact.

The solution developed by the student was to scrape the gum off the sidewalks using scrapers. However, as mentioned above, the size and shape of the scraper differed based on what surface it would be used. For sidewalks, for example, the student chose to use a bigger and wider concrete scraper that is beveled at the edge, similar to a knife. The scraper was six feet wide, and could be adjusted to change the angle, and was to be operated by two people. For benches, trash cans, and signs they chose to use "regular" scrapers, without giving any details. To remove the gum from stairs, they chose to use a scraper attached to a broom handle, considering that people would need to bend over on stairs and that their backs may hurt if using a regular scraper. In addition to the idea of scraping, they also discussed prevention methods such as putting a note on wood benches that says "Do not disturb" and adding more trash cans in the area to prevent gum on the streets. Overall, the final solution formulated by the student was manually scraping the gum off later at night starting with the benches, signs, stairs, and trash cans first, which they reasoned might take slightly longer, and then the sidewalks second.

Analysis of Faculty

The faculty participant spent 28 minutes to complete solving the problem and, unlike the student, asked clarification questions such as whether they could use the Internet or other resources, and if they needed to talk to themselves. Upon reading the problem, the faculty solved the problem by investigating methods for gum removal, and initially considered two potential solutions. These solutions consisted of manual removal of gum and using some type of equipment to remove it. They started by comparing these two methods in terms of how much time each would require and how much each would cost. They explicitly stated what they considered during the problem solving process, stating "*I would compare the available methods for removing gum, estimate the resources required for full scale implementation, the number of workers required, and the amount of equipment required*."

Different from the student participant, the faculty chose to first assess approximately how much gum removal is required and in what locations, and then test their solution in a few locations in the park to see whether their method was suitable and cost-effective and to examine the rate of removal. The faculty also spent time discussing the feasibility of their solution, including which season and climate condition to implement the solution and whether lighting would be an issue during night conditions. Similar to the student, the faculty picked the same testing location which was isolated from water bodies and busier paths and roads. Without being prompted to do so, they ended the problem solving process with a short summary of the final solution. No *hypothetical processes* or *connection to outside knowledge* were used. *Participant feelings* and *double checking* occurred only once each throughout the problem solving process. Since the solution was to use small handheld tools for removing the gum, they expressed their feelings about the problem by saying "*Okay, um, and I'm struggling a bit with some of these constraints. It seems like the problem is suggesting the use of large equipment and I am just not- not connecting in terms of how you would use large equipment for this*." This was the only time the faculty expressed feelings. The faculty double-checked themselves through the end of the problem solving to see if testing the solution under different conditions was allowable.

As their final solution, the faculty participant selected the use of small handheld tools for removing gum in a team of two to three individuals who would rotate through the area on a nightly basis during periods when the park was closed. What was noted was that they paid great attention to climate conditions, lighting during implementation, and using environmentally safe materials and all of these occurred while they discussed the feasibility of their solution. Weather conditions played an important role in the faculty's design process. They chose to implement their solution in the fall before the snow comes and in the spring. In addition, as they proposed to implement the solution during night when the park was closed, they wanted to ensure that people would have enough lighting to scrape the gum. They also chose to use chemicals to help with the removal of gum as long as they were environmentally safe.

Analysis of Practicing Engineer

The practicing engineer spent all the available allocated time to solve the ill-structured problem and while working on the problem asked a clarification question which was about whether the solution should be related to structural engineering. They began solving the problem by expressing their feelings "*Okay. So, um, initially, I'm not really sure what I'm supposed to be designing*." They then introduced an initial solution which was to use a type of non-toxic chemical to loosen the gum and scraping the gum off. The beginning of the problem solving process consisted heavily of going back and forth between the provided *problem statement* and *idea expansion*. For example, they discussed when to start testing and then re-read the directions and problem prompt. They selected an isolated location for implementation to have less impact on people and environment, and proposed to implement their solution at night twice in the summer, citing that parks are more heavily used in summer months. The practicing engineer spent a great deal of time expanding on their idea, which consisted of what material to use for the scraping equipment, what size it should be, and where to test their proposed solution. Adding safety lights to the implementation area played an important role in the practicing engineer's solution and was emphasized a few times within their solution. Although they were not allowed to use the Internet, they suggested googling what other cities had done, what had worked best for them, and what had not worked. No *hypothetical process*, however, was found within the practicing engineer transcript.

As their final solution the practicing engineer proposed to loosen the gum first using environmentally-friendly chemical sprays pulled on a small trailer, and in addition, to have volunteers scrape the gum off using a machine. The equipment they described would be maintenance equipment with attachments similar to a "snow scraper", skid-steer, or sweeping machine. For the benches, trash bins, stairs, and signposts they recommended using smaller scrapers. They also focused on prevention methods and suggested raising awareness of the problem by putting more trash cans in the park similar to installing "dog waste stations".

It was noted that the practicing engineer commonly used questions, directed at themselves, such as "*Still unclear of how to get the gum off. Um are you supposed to scrape it, or--?*" throughout the problem solving process. Another notable trend within the transcript was the consecutive use of *idea expansion* followed by *feasibility*. This was mostly completed by expanding on an idea first (i.e. providing more details about an idea such as calculations) and then discussing its pros and cons or workability, which was followed by returning to idea expansion. *Participant feelings* were also found to be used by the practicing engineer during the problem solving process. "*I don't know*" and "*I am not sure*" were the two most commonly used expressions, such as in the following examples: "*Uh, I am not sure what's the kind of equipment they use*" and *I don't know about gum removal*."

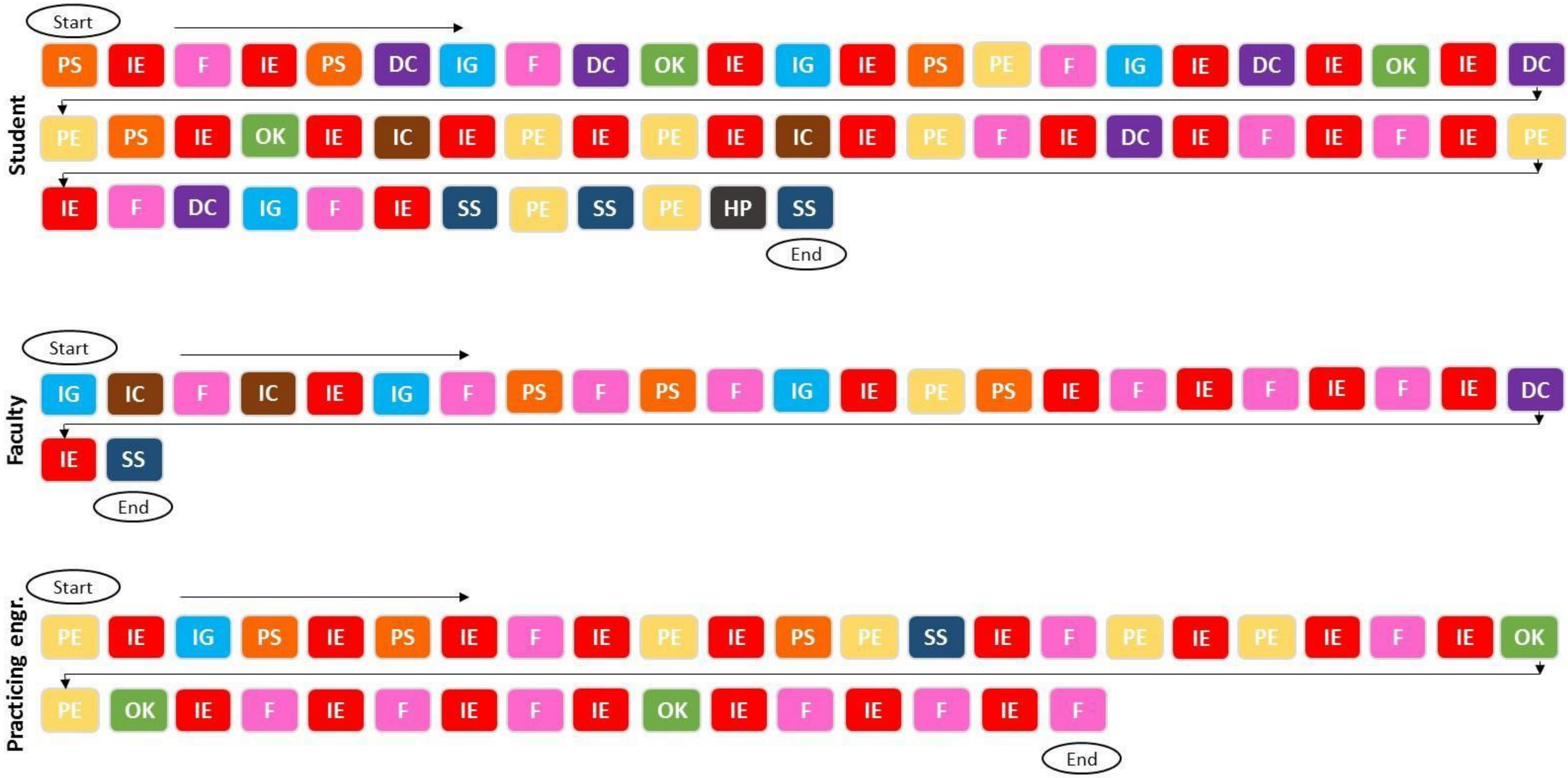

Figure 2. Problem solving steps taken by participants. DC = Double-Checking, F = Feasibility, HP = Hypothetical Process, IC = Idea Comparison, IE = Idea Expansion, IG = Idea Generation, OK = Connection to Outside Knowledge, PE = Participant Emotions, PS = Problem Statement, SS = Solution Selection.

Figure 2 shows the chronological order of the problem solving steps adopted by each participant from the beginning to the end of the problem solving process. As shown in the figure, problem solving processes of the student, faculty, and practicing engineer showed both similarities and differences. While the student was found to use all the codes listed in Table 2, the faculty and the practicing engineer were observed to use fewer codes. Within all the participants' solutions, *problem statement* was found to occur at the beginning of the problem solving process. The use of the *idea expansion* step followed by *feasibility* was a common trend in the participants' problem solving processes, particularly within the practicing engineer's solution. Unlike the student and faculty, the practicing engineer selected their solution in the middle of the problem solving process and used the remaining time expanding on their ideas and feasibility. The student and the faculty, however, chose to select their solution at the end of their problem solving process while first discussing feasibility of their initial ideas and expanding on them. In addition, *hypothetical process* was only found within the student's solution.

IV. Conclusion

In this study, the main goal was to investigate the approaches that a student, faculty, and practicing engineer in civil engineering took to solve an ill-structured engineering problem and describe their problem solving processes. Both similarities and differences between the student, faculty, and practicing engineer were found.

All three participants generally developed the same solution, i.e. scraping the gum off using scrapers, but the level of detail differed. Both the student and the practicing engineer chose to use a bigger scraping tool for sidewalks, while using smaller tools for the other areas in the park. In addition, the student and the practicing engineer chose to increase the number of trash bins on the streets for prevention purposes. The faculty, however, proposed the use of a single scraping tool for all surfaces and did not mention prevention. All the participants selected the same location and time for implementing their solutions to protect the environment and people in the area. The student spent most of their time providing details regarding why a different size and type of tool was used for each type of surface, while the faculty and the practicing engineer were more concerned with feasibility and safety issues. They focused more on climate conditions and using safety lighting and environmentally friendly chemicals during implementation to scrape the gum off. Weather conditions were also important for the faculty and the practicing engineer to consider for implementing their solutions, whereas the student did not discuss these aspects of their solution.

The faculty was found to express their emotions less than the student and the practicing engineer did. In addition, the student and the practicing engineer used their background knowledge to support their problem solving process, while no *connection to outside knowledge* was discussed by the faculty. The student and the faculty ended their problem solving processes with a solution summary briefly describing their solution, whereas the practicing engineer ended with a discussion of *idea generation* and *feasibility*. In addition, both the faculty and the practicing engineer chose to develop a specific solution (i.e. *initial idea*) right after reading the problem statement, whereas the student spent time expanding on ideas, reading the problem, discussing feasibility, and double-checking prior to developing a solution.

In summary, we found that the participants' approaches to the ill-structured problem varied, which was consistent with the findings of Atman et al. [20] who also found variability in the design behavior of students and faculty. This study identified steps associated with solving an ill-structured problem in an engineering context and a way to present how different steps are adopted in the problem solving process. Our findings can be used by other researchers to study ill-structured problem solving processes of different participant groups in different contexts. The findings and analyses presented in this study help to understand the similarities and differences between a student, faculty, and practicing engineer in terms of their design processes, but are only limited to three participants. Given the variability of the design processes across the participants, further studies focused on understanding the similarities and differences between students, faculty, and practicing engineers' problem solving processes are needed across a larger dataset. Another limitation of our study is that because this paper is part of a larger study, the size of the institution each participant attended was not standardized, which may impact the findings of this study. This variable will be considered further in future studies.

Moving forward, the research team will continue to collect and analyze additional data as part of an ongoing study to better understand these design processes, and to generalize our results across participant groups. We are also examining factors such as self-efficacy and learning styles that may influence participants' problem solving processes. One of our goals is to apply our findings to developing course modules to teach undergraduate engineering students appropriate problem solving approaches as well as informing engineering faculty about better ways to teach the solving of ill-structured problems. It is our hope that these efforts will provide a way to better understand problem solving approaches adopted by students, faculty, and practicing engineers.

Acknowledgements

This work was funded by National Science Foundation Grant DUE #1712195. The project is entitled "Collaborative Research: Bridging the gap between academia and industry in approaches for solving ill-structured problems". Data, findings, and conclusions or recommendations are those of the authors, only. We acknowledge and thank Mary Anton, undergraduate research assistant, for her efforts to code the transcripts.

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