Modeling Student Problem Solving for Improving Project-Based Learning

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Abstract
Project-Based Learning courses are widespread in engineering curriculums worldwide. As such, understanding how students problem-solve in these settings benefits curriculum designers, educators, and future learners. The objective of this research was to employ a human factors approach of modeling and error analysis to develop and apply a cognitive model to illustrate how students make decisions and problem-solve in a Project-Based Learning course. In addition, the Systematic Human Error Reduction and Prediction (SHERPA) was applied to identify errors in the process illustrated through the model. Data was collected from direct observations of 84 students in the classroom over two terms, along with qualitative reflection surveys and individual interviews to understand the project's impact on their problem-solving skills during their studies. The final model can be extended to other PBL courses to allow the targeted design of course materials to fit the student problem-solving processes, improve the project, and thereby improve learning outcomes. One main finding of this study was that students consistently failed to predict consequences, and predominately relied on each other as well as course PowerPoints to solve any problems that arose, illustrating the value in developing processes for improved materials.

Keywords: engineering education, Project-Based Learning, cognitive model, decision ladder, error analysis.

Introduction

Since Project-Based Learning (PBL) has been widely adopted in engineering education, it is imperative that instructors learn more about PBL to benefit learners in the classroom (Chen et al., 2021). PBL is a learning method where students are exposed to real-world projects in the classroom (Yusof et al., 2012). Students are given hands-on projects on day one, where they are given the ability to develop communication skills, critical thinking, and address complex questions (Yusof et al., 2012). PBL can be stressful for students as it requires skills such as proper communication, critical thinking, and problem-solving, which students may develop while actively working on their projects (Mohd-Yusof, 2014). Since every student learns at their own pace, PBL may not be the most appropriate learning technique because they may not have received the necessary support, background, or attention needed to thrive in PBL (Mohd-Yusof, 2014). However, PBL has also been shown to be more effective than traditional learning in the classroom (Luke et al., 2021; Hendry, 2016; Greiff, 2013). Traditional learning does not equip the student with the necessary skills to solve real-life problems; however, PBL does (Henriksen, 2009). Much research has been done not only on PBL but also on how to effectively implement PBL in an engineering classroom (Mills & Treagust, 2003; Gonczi & Maeng, 2020; Fink et al., 2002), as well as and shown success with PBL in classrooms in other disciplines (Clausen, H. B & Andersson, 2019; Ding et al., 2014; Jin & Bridges, 2014; Alrahlah, 2016).

Many engineering jobs require problem-solving skills. The primary purpose of the use-case project described here is to teach students skills they may use in their future engineering careers. The instructor hopes to cultivate communication skills, critical thinking, and problem-solving abilities in interdisciplinary teams, as is needed to excel in industry jobs (Nguyen, 1998). Although the plotter project is implemented in a mechanical engineering course, the project incorporates skills that may not be typically seen in a mechanical engineer's skill set. The plotter project provides engineering students with different skill sets, such as coding, manufacturing, and building that they can use in their future careers.

Even though much research has been done on PBL in engineering education, including social interactions with others in a PBL classroom (Sedaghat, 2018; Du & Kolmo, 2009), this study provides a novel approach using human factors tools and methods to improve design of course materials, through the development and application of a cognitive model to illustrate how students approach decision making in a PBL course. An error analysis, aligned with the model, was applied

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to identify common errors encountered in the process. Our approach considers both aspects to address the following research questions:

1. Do students follow a problem-solving model that could be useful for instructors in a Project-Based Learning course?
2. Does the quality of resources and social experience with fellow students influence how a student problem-solves in an engineering classroom?

Figure 1 illustrates the human factors approach taken that will be described in the following sections.

First, an introduction to the relevant background is provided, along with a description of the PBL course and project presented as a use case. The cognitive models developed are next described in detail, followed by the methodology of observations, interviews, and surveys to provide relevant data for revising the model, the SHERPA for error analysis, and finally, recommendations based on the findings from this work for improving PBL course projects.

Background

Problem-solving in the Classroom

The ability to effectively problem solve is a key skill that students must have to do well in the classroom and their future careers (Greiff, 2013). The project implemented in the class requires students to know how to solve problems effectively. However, some students tend to struggle with being able to solve problems in the classroom, predominantly because of difficulties working well with other students. Students may struggle to work with others because of social or cultural issues such as gender, previous experience, or previous friendships (Sedaghat, 2018).

Even though the project is an individual assignment, students are encouraged to work together on any problems that arise. Much research has been done on how to set students up for success when working in teams in an engineering classroom (Sedaghat, 2018; Rodríguez-Simmonds, 2018). Finelli et al. (2011) discusses the ample research that has been done that highlights the benefits to students of effective teamwork both during coursework and in a professional setting. Good teamwork plays a crucial role in effective problem-solving, which is highlighted in the proposed model.

Many studies have been done to show the benefits of problem-based learning in the classroom (Maker, 2020; Gonczi & Maeng, 2020; Luke et al., 2021; Hendry et al., 2016; Greiff et al., 2013). Some benefits are that students are given the opportunity to gain theory, content knowledge, and comprehension, as well as help students learn creative thinking, problem-solving, and communication skills (Awang & Ramly, 2008). Wegner et al., (2015) collected data to understand better how students worked together in a team for a design project. In the final assignment, students were asked to reflect on critical milestones in their personal development during their design projects. With these milestones identified, researchers could see common themes that impacted the students the most. The results of this study have been utilized to enhance how instructors teach engineering design to benefit the students most in their future professional careers.

Cognitive Models (Decision Making Model and PBL Model)

Modeling, a cornerstone of human factors research, involves creating representations of human-system interactions to predict performance and identify areas for improvement. In the context of engineering education, several types of models have shown promise, including, cognitive task analysis (CTA), information processing models and models from mental model elicitation. CTA models break down complex cognitive processes, such as those involved in learning engineering concepts, helping instructors identify potential areas of difficulty for students (Kirwan & Ainsworth, 1992). Information processing models are based on the flow of information as it is processed by the human brain (Wickens 2021). By mapping how students perceive, process, and retain information, these models can inform the design of

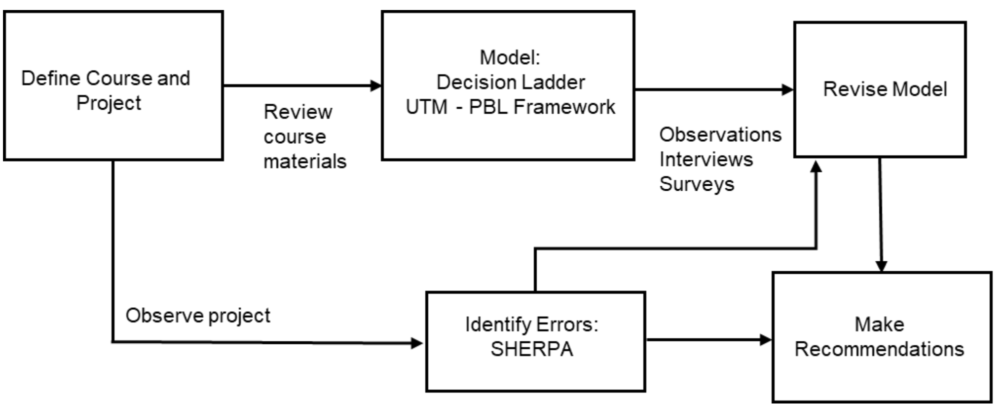

Figure 1. Research approach using human factors tools and methods of cognitive modeling and human error analysis.

lecture materials and learning activities (Johnson et al., 2023). Mental models can help instructors understand students' pre-existing conceptual frameworks, enabling more targeted and effective instruction (Vogel-Heuser *et al*., 2019). The decision ladder model incorporates several of these concepts by presenting the information processing steps and states of knowledge required by an operator to make decisions and ultimately achieve a stated goal (McNeese, *et al*. 1999; Jenkins *et al*., 2010). Any of these models can be constructed as normative or descriptive and both are important in understanding the student decision making processes. Normative models describe "norms" or "what people should do (in theory)". Descriptive models describe what people actually do or have done, and prescriptive models describe what people should and can do (Baron, 2004). A normative model (Figure 3) was initially created to better understand how students problem-solve and make decisions. Jaušovec (1994) showed that students who understand their thought processes when solving problems tend to solve problems better. Mental models also explain how students understand concepts differently (Ibrahim & Rebello, 2013). For this reason, a cognitive model is beneficial for instructors to understand how students problem-solve and design their project components accordingly. This model incorporates elements of the Decision Ladder model, (Jenkins et al., 2016) which supports activities like situation analysis, goal selection, as well as planning and execution (Naikar, 2010), and the Universiti Teknologi Malaysia (UTM) cooperative PBL framework (Yusof et al., 2012). We chose the Decision Ladder model since students were required to plan out the steps of completing the project as well as actually completing the project. Students were also required to diagnose and fix any issues that arose when completing the project. We chose the UTM cooperative PBL framework since the course is a PBL course. Both models were used to develop this cognitive model, since both problem-solving and decision-making are critical elements for the successful completion of the project.

Contributions of this Study

This study uses human factors tools and methods to extend the engineering education literature by providing researchers with a framework to understand student problem solving and recommendations to support the development of PBL activities for the engineering classroom. Using normative models to evaluate user behaviour and modifying the models based on actual user behaviour results in descriptive models to help instructors in PBL courses adapt their projects to suit the needs of learners. Instructors will also be able to better adapt the resources given to students in engineering classrooms to help students effectively solve problems. This model can be adapted and extended to represent PBL processes in classrooms around the world to suit educational and cultural differences.

Methods

This study was conducted through a series of observations, surveys, and interviews in a junior-level engineering class (Manufacturing Processes) at a university over two terms. The course materials were reviewed to develop the initial decision making model, while the observations, surveys and interviews were used to validate and revise the model. An error analysis was also conducted to understand the implications of the decisions over the sequence of steps of the project completion.

Participants

Manufacturing Processes is a required class for Mechanical and Industrial Engineering majors. However, other engineering majors may enroll in the course. There were 84 students (71 male, 12 female, 1 no response) who participated in this study over two terms. There were 44 students who participated in the Winter term and 40 students who participated in the Spring term.

Materials

This course was structured as a series of lectures, quizzes, and the PBL activity. The project, building a plotter, was completed over a period of eight weeks. Throughout the project, students followed PowerPoint instructions to complete the plotter. The project provides students with two opportunities to create a design solution throughout the project, allowing students the opportunity to explore a real-world problem creatively. The students are first asked to create a design from scratch for their pen holder. They are then required to determine what graphic to use and how to modify code for the plotter to draw the chosen graphic. Figure 2 illustrates an overview of the steps of building the plotter.

Procedure

Due to a delay in Institutional Review Board (IRB) approval, observational data was collected over a 4-week period in the first term. During the second to last week of the term, a survey was administered to the students (seen in Appendix A). Going into the Spring 2022 term; the survey was revised to elicit more quantitative results, with some questions being converted into Likert Scales. Observations were collected over 8 weeks in the second term. The revised survey can be seen in Appendix B. The error analysis, specifically the SHERPA, was conducted using course materials, and the results of the observations and was used as input to revising the final descriptive model of decision making.

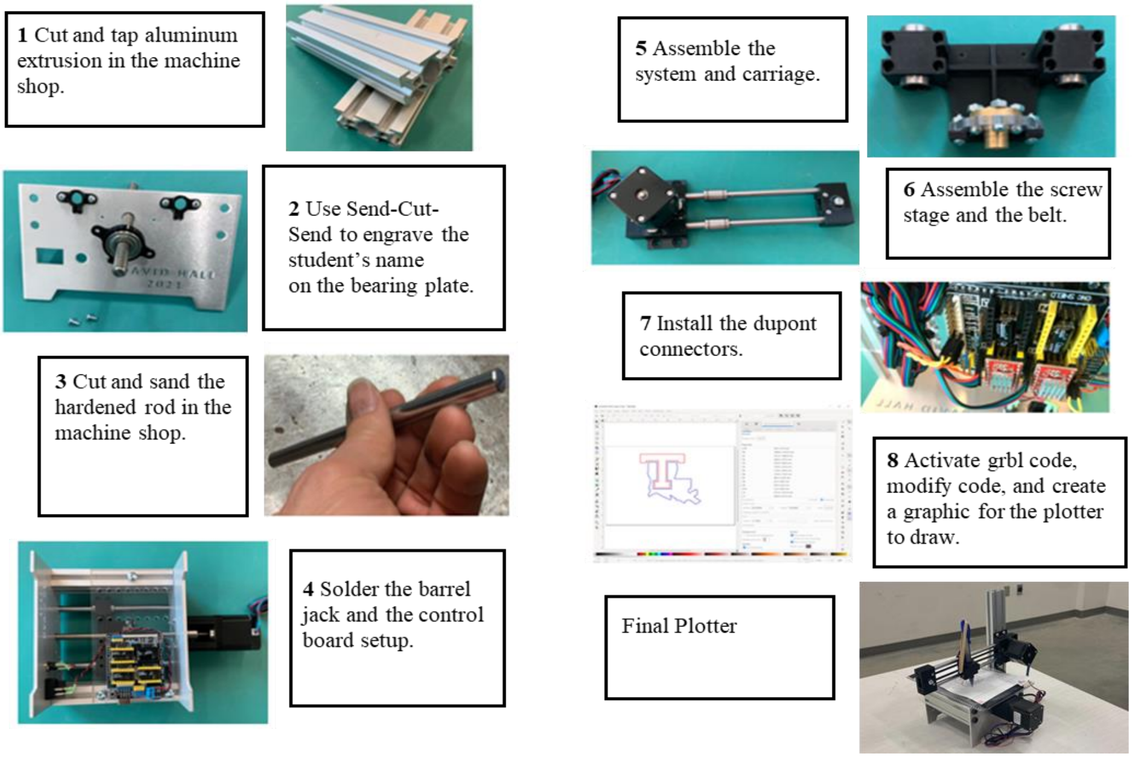

Figure 2. Overview of steps students follow to complete the plotter project

Surveys were given out in the second to last week of the quarter. By this point, most students were done with building their plotter. The only step any of the students had left to complete was to implement the code for their plotter to write/draw. The survey gathered demographic information in addition to questions regarding the project approach. Since the qualitative data is observation-based, the researchers of this study wanted to make sure to have responses from every student. This allowed the researchers to have more quantitative data to analyze to help validate the study's results. Likert scale questions were also given on the survey to have an overall mean of how confident students felt when problem solving.

Interviews were conducted with six students, in a subsequent term, who had previously taken the course, to gain insight into how they thought the project had impacted their engineering education so far. After the Winter term, an email was sent to the students who completed the class asking if they would be willing to be interviewed on their experiences in the class. Six students agreed to be interviewed. During the interview, the students were asked three Likert Scale questions and a series of open-ended questions that can be seen in Appendix C. Overall, the interview responses provided the researchers insight into how the use-case PBL project helped the students in future classes as well as if the PBL project provided them with more confidence in their problem-solving skills. Based on the student's responses, instructors of future course iterations will know how to tailor the project more to help their students develop more problem-solving skills.

Results

Data was aggregated from the observations, surveys, and interviews for the cognitive model, to answer the following research questions: 1) *Do students follow a problem-solving model that could be useful for instructors in a Project-Based Learning course? And 2) Does the quality of resources and social experience with fellow students influence how a student problem-solves in an engineering classroom?*

For the first research question, a cognitive model was created and evaluated to determine if students follow the problem-solving model in a PBL course. The resulting model was based on an aggregation of existing models in the literature (Jenkins et al., 2016 & Yusof et al., 2012). The model was validated through a combination of in-person observations and the survey and interview results. To answer second research question, the researcher directly observed the students, taking notes on how students interacted with the resources and fellow students in the classroom. To analyze the qualitative data, the method of thematic content analysis is used, where the researcher reviews the data, analyze the themes within the data, and then compiles the main themes into groups (Burnard et al., 2008). The data included the output of the SHERPA analysis.

This section describes the results of creating the initial model, the output of the SHERPA analysis, and quantitative analysis from the surveys to arrive at the final, validated model that can be used for designing PBL materials.

Normative Model

The resulting model describing how students should make decisions is shown in Figure 3. For the model, students first meet the problem of how to build and design the plotter. They then start to make decisions, by first determining the final goal of the project. After being alerted about needing to make a decision, students should begin to find the information needed to solve the problem and complete the task. Students will then determine if the system is working properly. Based on the system's state, the students should look at their available options. They may change the system state based on these options to accomplish the overall goal by predicting any potential consequences. They then test their system to evaluate its performance. Next, they plan and execute the remaining tasks to build their plotter. At the end of the project, students reflect on their work to gain closure on the project.

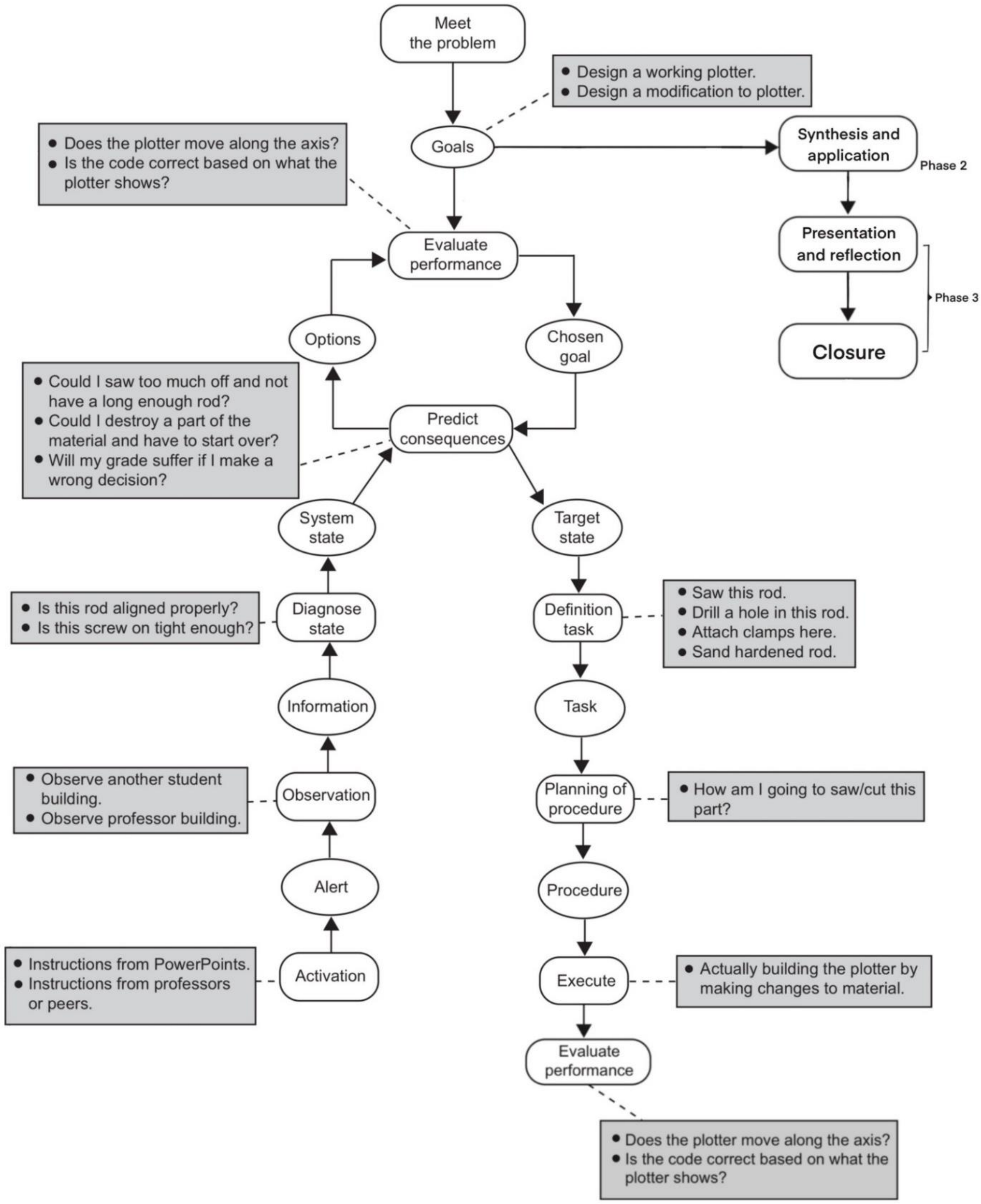

Figure 3. A decision ladder model incorporated into a problem-based learning framework

The ultimate purpose is to make recommendations on improving the instructional materials and process for this project based on how student learners' problem-solve and make decisions. Having a model that highlights decision points and problem-solving opportunities will improve the experience in PBL courses since instructors will know how to better design their PBL courses. For example, this model shows the order of steps that students partake in which will allow instructors to properly design their projects and course design to meet these steps. One of the main things seen is that students do not always predict consequences which is a crucial step as seen in the cognitive model. Knowing this, instructors can make sure to specify any potential consequences that could result when implementing a certain task of their project. Instructors may even add an extra slide at the end of each PowerPoint showing what could go wrong if the project step is not executed properly.

Throughout both terms, we observed that the students failed to predict consequences. For example, one student noticed he had a wobbly surface once he started to run the plotter. When questioned about the wobbly surface, the student admitted that he did not predict this could happen. He realized that he had not tightened one of the screws enough, which caused his board to wobble. Another student failed to predict his screws would roll off the table. However, after seeing this happen, the next class he decided to bring a paper plate to hold his screws since he noticed that everyone was losing screws since they would roll off the table.

Error Analysis

As students consistently failed to predict consequences, the researchers of this study applied the systematic human error reduction and prediction approach (SHERPA) analysis (Embrey, 1986). The SHERPA utilizes an error mode taxonomy to classify errors. Each error mode described in the SHERPA table has the same id as seen in a SHERPA table. For example, A9 corresponds to "Operation incomplete" (Embrey, 1986). The SHERPA table allows the instructor to see where and how errors are occurring, the consequence of these errors, the potential for recovery, the probability (P), and the criticality (C) of the error. The SHERPA table also provides remediation strategies for items that can be addressed in class to increase the potential for learning and project success. If students are given the proper instruction for the PBL activity, students will be able to learn more from the activity while experiencing less frustration.

Table 1. SHERPA (P and C columns refer to levels of low, medium, or high probability and criticality respectively) Each error mode has an assigned mode given by a letter and number, along with a mode description

Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
A9-Operation incomplete	Failure to properly tap the holes	Screws will not tighten- will wobble	None	L	H	Provide training on how to tighten screws properly; demonstrate for the class what one should look for
A4-Operation too little/much	Cutting the black wire attached to barrel jack	Wires will not be long enough to reach power input on CNC shield	None	L	H	Instruct the students on the length required and make the students measure before cutting
A4-Operation too little/much	Failure to set correct temp for solder	Solder will not be hot enough to properly solder the wires	Immediate	M	L	Instruct the students on the correct temperature settings
A6- Right operation on wrong object	Wrong screw used	Part will not fit snugly together	Immediate	H	L	Provide clearer pictures/labels of the screws needed; Provide training on how to properly measure the size of the screws
A6- Right operation on wrong object	Wrong drill bit selected to size holes	Given screws will not fit	None	M	L	Provide clearer pictures/labels of the drill bit needed; demonstrate how to properly select the drill bit

A5- Misalign	Extrusion of aluminum not cut properly	Plotter will not sit flat- will wobble	Immediate	L	M	Provide training on how to properly cut the aluminum; demonstrate cutting steps
A1- Operation too long/short	Stripping screws	Will need to replace screws	Immediate	M	L	Provide training on how not to strip screws; demonstrate correct motions to the students
A9- Operation incomplete	Failure to properly code	Plotter pen will not move properly	Immediate	H	H	Provide training on how to code; provide trouble-shooting resources for students

Observations

Overall, through direct observations conducted by the main researcher of this study, the researchers found that the social experience with fellow students does influence how a student problem-solves in the classroom. Survey feedback indicated that students solved problems differently based on the resources they were given. The focus was to observe how students approached problem-solving and used available resources. Throughout the term, data was collected by observing the students building their plotters in the classroom. The researcher observed that most students would ask their peers questions when trying to solve problems that arose.

Some students worked by themselves and mostly utilized the PowerPoints provided. Other students asked the professor for help if they could not figure it out. Having fewer social interactions impacted how these certain students approached the project as they chose to rely on their own ideas instead of reaching out to other people in the class. In the Spring term, one student ended up super frustrated and angry when told by the professor that he put together a part of the plotter wrong and needed to work backward to fix the issue. This particular student was working at a table by himself, and one can say that part of his frustration was caused by not having anyone at the table to help him solve problems. Almost all students only asked the professor for help as a last resort. Overall, students tended to rely on the PowerPoints and each other to decide how to build their plotter and solve any problems that arose throughout the execution of the project.

Surveys

The results of the surveys showed that when solving problems, most students asked their classmates how to build certain parts of their plotter. Table 2 shows, from most commonly used to least, the approaches observed. These results aligned with the observations seen in the classroom. Seven students stated that they reached out to past students rather than ask the instructor. Since students tended to ask other classmates, students who did not have previous relationships with classmates would problem solve on their own versus asking for help from other students. The model *identifies* opportunities in the process where students need information to diagnose the system state and plan procedures to reach the target state.

Table 2. Preferred problem-solving approaches in PBL classroom (from student surveys)

Problem-Solving Approach	**Number of Times Employed by Students**
Ask Classmates	54
Online Search	19
Ask Instructors	11
Ask Previous Students	7
Course Material	3

Nineteen students stated that they tended to google solutions when problems arose, and only eleven students stated that they would ask their instructor first for help. Some students stated they would refer to the PowerPoints anytime they could not figure out how to do something in the building of the plotter. One particular student stated that he used a trial-and-error approach when solving problems. The student stated that he would try one solution and if the solution did not work, he would start over and try another solution until he eventually solved any problems that arose. Students also stated that they thought the GNC shield, and coding were the hardest part of the project, while the general assembly of the plotter was the easiest. Understanding student approaches and preferences allows instructors to provide better resources to help learners solve problems in a PBL course more effectively.

The survey was revised based on the students' responses during the Winter term by including three additional Likert scale questions (Table 3). Results indicate that all students felt at least moderately confident that they could solve problems as they arose. These results showed that students overall felt they could solve problems on their own which is a crucial skill that engineers must have, and should be supported by the PBL course resources.

Table 3. Student responses on a Likert scale of Not at all confident or clear to Extremely confident or clear

Questions	Mean	Standard Deviation
How confident were you that you could solve problems when they arise?	3.85	0.70
How confident did you feel working on this project on your own?	3.88	0.82
How clear were the instructions for you to be able to work on your own?	3.68	0.80

The next two questions asked students if they were confident in working on the project alone and if the instructions were clear enough for them to do so. The results show that the students were not completely confident about working on the project independently and felt that the instructions could be clearer. Updated PowerPoints with clearer instructions would allow future learners to work more independently on the project.

Interviews

Based on the responses of the students; we were provided with more evidence that the quality of resources and social experience with fellow students does influence how a student problem-solves in an engineering classroom. One of the students said: “This project would have been hard as a Freshman, but now, with experience, I could handle the project in a junior-level class. Made the class easier to be able to talk to other classmates since I knew people. Would have been hard to do the project if I did not know people. Connections are necessary.”

Many students spoke about the quality of resources given affecting their ability to complete the project. One student stated “One thing would be to update the PowerPoints. More pictures and in-depth steps would be nice. Some assembly pictures were not clear.” Another student stated “The instructions were not very clear in some parts. Would have changed it to make more straightforward instructions instead of having to assume stuff. Could tell that some stuff was not polished yet. Better raw materials, some of the stuff that we got, the lead screw bent which made it hard to have everything line up when you assembled everything. The surface wobbled because the lead screw was bent.”

Another student spoke about the instructor not being able to help with the coding, which affected his ability to problem-solve during the project. This student stated “I was enjoying the project until I got stuck with the coding. The professor was not able to help with the coding. He spent a lot of time troubleshooting the code. Wish we could have sorted out the issue faster.” Overall, based on the interview results, we can conclude that students’ interactions with one another and the quality of the resources given to them affected how they were able to problem-solve.

Descriptive Model of Student Problem-solving

The initial normative model was revised using all of the data gathered, resulting in the descriptive model shown in Figure 4. For the most part, students tended to follow the path of the initial model. However, there were several key changes. The first change was to take out the *predicting consequences* block in the model.

The students would not consider any consequences due to building the plotter incorrectly, and frequently had to re-do parts of their plotter after being told by the professor that they did something wrong, to make the plotter function properly. For example, as previously mentioned, students did not predict that their plotter would wobble if parts were not installed correctly. Students also did not predict that the screws would roll off the table if they did not put them in a safe place on the table. To correct this, the PowerPoints should show any potential errors resulting from the students building a part of the plotter incorrectly. The PowerPoints' quality influences how students solve problems based on the results we saw. An additional change was moving the *evaluate performance* block to the end of the model. It was observed that was the last thing students would do when building their plotter. Instructors can use this revised model to emphasize to students the importance of constantly and iteratively evaluating their project throughout the process instead of waiting until the end of the building to evaluate. This way, students can predict consequences and make any necessary changes with less frustration and better use of resources during the process. Using this revised model, instructors in other PBL courses will know to emphasize that students should thoroughly think through the potential consequences at each stage (or system state). Instructors will also know to tell their students to constantly check that their project components are working properly throughout the building process as fixing an issue will be much harder at the end of the project versus fixing issues throughout the building of their project.

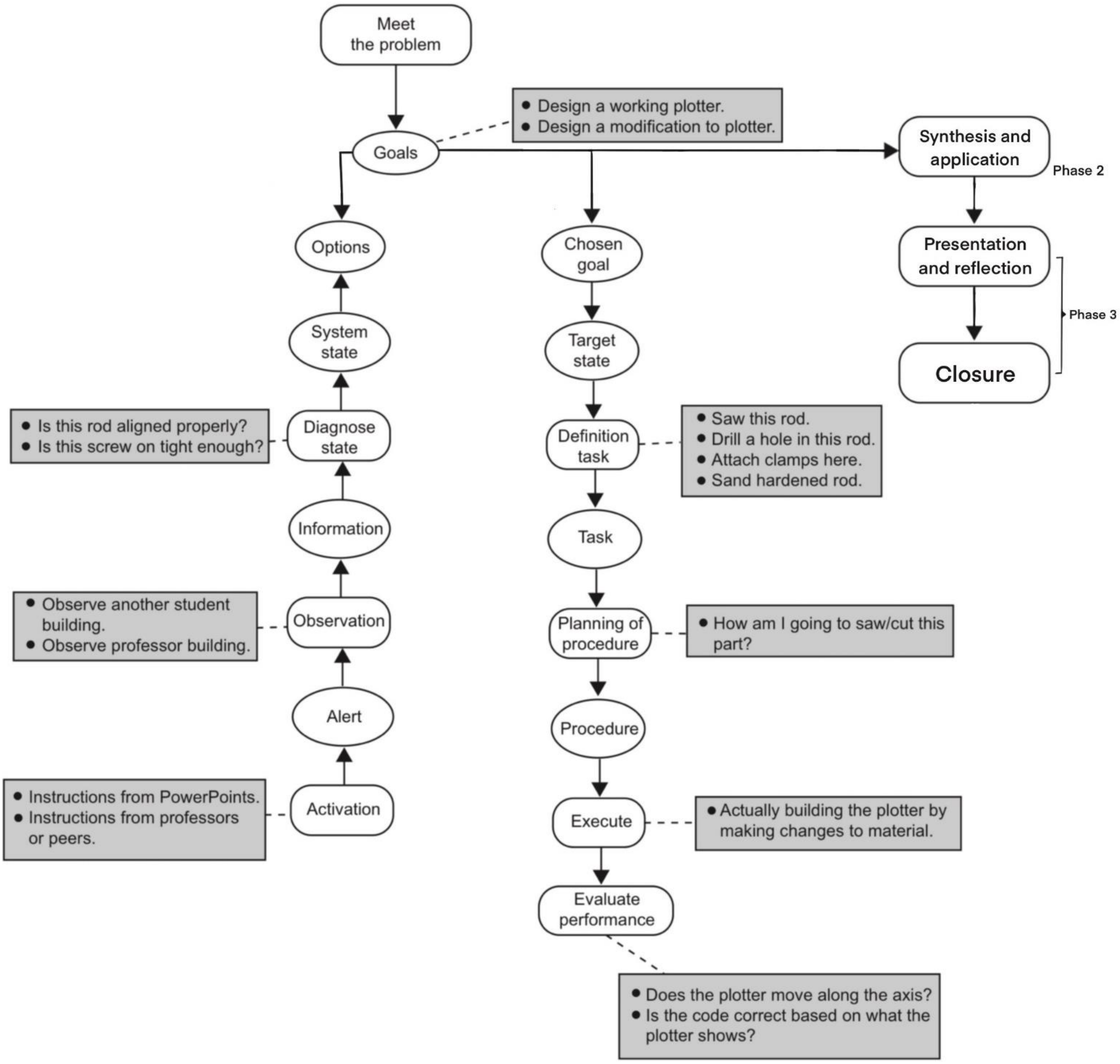

Figure 4. A revised decision ladder model incorporated into a problem-based learning framework based on results of the study. Shaded rectangles refer to specific examples related to the use case.

Discussion

This study employed a human factors approach to show how students make decisions and problem-solve during a PBL activity in an engineering classroom. As a result, instructors have a set of resources, a validated cognitive model, and SHERPA, that can be used when designing their project-based learning activities to benefit future learners. These resources are grounded on how engineering students approach problem-solving, as prior research has shown that PBL benefits learners in the classroom (Chen et al., 2021). The overall key findings of this research are that students failed to predict consequences throughout the project as well as waited until the end of the project to evaluate the performance of the plotter. Because of this, we recommend that future instructors in PBL courses emphasize to students to thoroughly check each component throughout the building of a project. We also recommend that instructors provide students with enough resources for them to accurately build their PBL projects. Generally, cognitive models are not widely seen in prior research studies in PBL studies. This research expands on these by integrating the UTM-PBL and decision ladder models to better illustrate how students actually problem solve during execution of these projects. The implications of this study will help both instructors and curriculum developers in PBL classrooms as they will know how students think and problem-solve. Application of the model and error analysis resulted in recommendations to aid curriculum developers and/or instructors in designing their PBL courses accordingly.

Using the output form the combination of observations, surveys and interviews, the following recommendations can be made. At the very least, it is recommended that the slides and other course materials be updated to visually depict what the students should be building and diagrams of the circuitry, etc., as we can see that the quality of resources influences how students solve problems. Providing these materials at the beginning of the project would provide an end goal of expected results. A physical, as well as a SolidWorks model of the completed plotter was also requested to help aid the students in the building of their plotter. Students also requested more resources for the coding aspect, as most people were unfamiliar with how to code their plotter. Even though this is specific to the use case, this holds true for many engineering projects that involve multiple skill sets. There is a need to provide supporting resources for secondary skills not necessarily taught in the course. These necessary skills have been shown in prior research to be critical for students to know how to apply (Nguyen, 1998). The last recommendation for the instructor is to have more precise due dates, or a timeline of expectations, on where the students should be in building their plotter so that they know if they are behind in the building process and can meet expectations (as seen in the cognitive model). Overall, if these recommendations are implemented, students should have a better learning experience when completing the project in the PBL course.

While this study has added to the literature on improving PBL in the engineering classroom, some limitations should be acknowledged. One such limitation, is that data was only collected in one PBL course, although it was collected over two different terms. Another limitation is that there was not a diverse group of students upon which to collect data, as most students in the course were mechanical engineering majors. Due to the majority of the data being qualitative, the researchers note that there may be some bias in the data observations and this should be noted. An addition limitation is that with a small research group, not all students could be observed during each class to have additional quantitative data, but this survey results for resource use aligned with what the researcher observed in the classroom, validating the responses.

Conclusions and Further Research

Since Project-Based Learning activities are more pervasive in the engineering classroom, providing instructors with a cognitive model of problem-solving and decision-making will allow the instructors to see how they should design their projects to fit the needs of the students. The model can be easily modified to fit many different types of engineering projects to support a broad spectrum of educational structures universally. Students can better grasp the course's concepts since the instructors have insight into how students problem-solve when completing a PBL activity. Additionally, instructors now have insight into useful aspects of their presentation material and resources for students to smoothly complete their project. Implementing the recommendations will provide students with clearer outcome expectations that can be visualized, support for secondary skills needed, and progress checkpoints to help improve learning outcomes.

For future work, recommendations will be given to the course's instructor to implement. Once these have been implemented, the study can be implemented again to determine if the students now have the appropriate resources to reduce frustration and improve resource use with the project. Applying the SHERPA output to other PBL activities, instructors can also design the project to help students predict consequences. By using the cognitive model, instructors in other PBL courses will be able to design their projects based on how engineering students problem-solve during a PBL activity.

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Conflict of Interest

The authors declare no conflict of interest.

References

Alrahlah, A. (2016). How effective the problem-based learning (PBL) in dental education. A critical review. *The Saudi Dental Journal*, *28*(4), 155-161. doi: 10.1016/j.sdentj.2016.08.003

Awang, H., & Ramly, I. (2008). Creative thinking skill approach through problem-based learning: Pedagogy and practice in the engineering classroom. *International Journal of Human and Social Sciences*, *3*(1), 18-23. doi: 10.5281/zenodo.1084906

Baron, J. (2004). Normative models of judgment and decision making. In D. J. Koehler, & N. Harvey, Blackwell Handbook of Judgement and Decision Making (pp. 19-36). London: Blackwell.

Burnard, P., Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Analysing and presenting qualitative data. *British Dental Journal*, *204*(8), 429-432. https://doi.org/10.1038/sj.bdj.2008.292

Chen, J., Kolmos, A., & Du, X. (2021). Forms of implementation and challenges of PBL in engineering education: a review of literature. *European Journal of Engineering Education*, 46(1),90-115. doi:org/10.1080/03043797.2020.1718615

Clausen, H. B., & Andersson, V. (2019). Problem-based learning, education and employability: a case study with master's students from Aalborg University, Denmark. *Journal of Teaching in Travel & Tourism*, 19(2), 126-139.

Ding, X., Zhao, L., Chu, H., Tong, N., Ni, C., Hu, Z., & Wang, M. (2014). Assessing the effectiveness of problem-based learning of preventive medicine education in China. *Scientific Reports*, 4(1), 1-5. doi: 10.1038/srep05126.

Du, X., & Kolmos, A. (2009). Increasing the diversity of engineering education–a gender analysis in a PBL context. *European Journal of Engineering Education*, 34(5), 425-437. https://doi.org/10.1080/03043790903137577

Embrey, D. E. (1986). SHERPA: A systematic human error reduction and prediction approach. In *Proceedings of the International Topical Meeting on Advances in Human Factors in Nuclear Power Systems*, 18(17), 184-193.

Finelli, C. J., Bergom, I., & Mesa, V. (2011). Student Teams in the Engineering Classroom and Beyond: Setting up Students for Success. Center for Research on Learning and Teaching. University of Michigan, paper 29.

Fink, F. K., Enemark, S., & Moesby, E. (2002, September). UICEE center for problem-based learning (UCPBL) at Aalborg University. In *6th Baltic Region Seminar on Engineering Education*, Wismar, Germany, 34-38.

Gonczi, A. L., & Maeng, J. L. (2020). Turn your PBL into an engineering-PBL!. *Science Activities*, 57(1), 25-32.

Greiff, S., Holt, D., & Funke, J. (2013). Perspectives on problem solving in cognitive research and educational assessment: analytical, interactive, and collaborative problem solving. *Journal of Problem Solving*, 5, 71-91. doi: 10.7771/1932-6246.1153

Hendry, A., Hays, G., Lynch, D., & Challinor, K. (2016). Enhancing student learning through Project Based Learning (PBL) in a secondary school integrative STEM course. AAEE Conference, Coffs Harbour, Australia.

Henriksen, L. B. (2009). Problem Based Learning and Instrument Realism: On Engineering Science, Engineering Science Theory and Engineering Education. In *Research on PBL Practice in Engineering Education*, 23-34.

Ibrahim, B., & Rebello, N. S. (2013). Role of mental representations in problem solving: Students' approaches to nondirected tasks. *Physical Review Special Topics-Physics Education Research*, 9(2), 1-17. doi:10.1103/PhysRevSTPER.9.020106

Jaušovec, N. (1994). The influence of metacognition on problem-solving performance. *Review of Psychology*, 1(1), 21-28.

Jenkins, D. P., Boyd, M., & Langley, C. (2016). Using the decision ladder to reach a better design. In The *Ergonomics Society Annual Conference, 19-21 April*.

Jenkins, D. P., Stanton, N. A., Salmon, P. M., Walker, G. H., & Rafferty, L. (2010). Using the Decision-Ladder to Add a Formative Element to Naturalistic Decision-Making Research. *International Journal of Human-Computer Interaction*, 26(2-3), 132–146. doi: 10.1080/10447310903498700

Jin, J., & Bridges, S. M. (2014). Educational technologies in problem-based learning in health sciences education: a systematic review. *Journal of Medical Internet Research*, *16*(12), 1-14. doi: 10.2196/jmir.3240

Kirwan, B., & Ainsworth, L.K. (Eds.). (1992). A Guide to Task Analysis: The Task Analysis Working Group (1st ed.). CRC Press. doi: 10.1201/b16826

Luke, A. M., Mathew, S., Kuriadom, S. T., George, J. M., Karobari, M. I., Marya, A., & Pawar, A. M. (2021). Effectiveness of problem-based learning versus traditional teaching methods in improving acquisition of radiographic interpretation skills among dental students—a systematic review and meta-analysis. *BioMed Research International*. doi: 10.1155/2021/9630285

Maker, C. J. (2020). Identifying exceptional talent in science, technology, engineering, and mathematics: Increasing diversity and assessing creative problem-solving. *Journal of Advanced Academics*, 31(3), 161-210. doi:10.1177/1932202X20918203

McNeese, M. D., Bautsch, H. S., & Narayanan, S. (1999). A Framework for Cognitive Field Studies. *International Journal of Cognitive Ergonomics*, 3(4),307–331. doi.org/10.1207/s15327566ijce0304_3

Mills, J. E., & Treagust, D. F. (2003). Engineering education—Is problem-based or project-based learning the answer. *Australasian Journal of Engineering Education*, 3(2), 2-16.

Mohd-Yusof, K., Phang, F. A., & Helmi, S. A. (2014). How to develop engineering students' problem solving skills using cooperative problem based learning (CPBL). *Engineering Leaders World Congress on Engineering Education*, 2014(3), 30. doi: 10.5339/qproc.2014.wcee2013.30

Naikar, N. (2010). *A comparison of the decision ladder template and the recognition-primed decision model*. (DSTO Tech. Rep. DSTO-TR-2397). Fishermans Bend, Victoria, Australia: Air
Operations Division.

Nguyen, D. Q. (1998). The essential skills and attributes of an engineer: A comparative study of academics, industry personnel and engineering students. *Global Journal of Engineering Education*, 2(1), 65-75.

Rodríguez-Simmonds, H. E., Jackson, B. P., Pearson, N. S., Langus, T. C., Major, J. C., Kirn, A., & Godwin, A. (2018). Interpersonal interactions that foster inclusion: building supports for diversity in engineering teams. In *ASEE Annual Conference & Exposition.* June 2018*.*

Sedaghat, A. (2018). Factors affecting the team formation and work in project based learning (PBL) for multidisciplinary engineering subjects. *Journal of Problem Based Learning in Higher Education*, 6(2). doi: 10.5278/ojs.jpblhe.v6i2.2002

Vogel-Heuser, B., Loch, F., Hofer, S., Neumann, E.-M., Reinhold, F., Scheuerer, S., et al. (2019). Analyzing students' mental models of technical systems. in 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), Helsinki, Finland, 1119–1125. doi: 10.1109/INDIN41052.2019.8972071

Wegner, J., Turcic, S. M., & Hohner, G. (2015, June). Learning from Experiences: Examining Self-Reflection in Engineering Design Courses. *2015 ASEE Annual Conference & Exposition*, 26-1066.

Wickens, C. (2021). Attention: Theory, principles, models and applications. International Journal of Human-Computer Interaction, 37(5), 403–417. doi:10.1080/10447318.2021.1874741

Yusof, K. M., Hassan, S. A. H. S., Jamaludin, M. Z., & Harun, N. F. (2012). Cooperative problem-based learning (CPBL): Framework for integrating cooperative learning and problem-based learning. *Procedia-Social and Behavioral Sciences*, 56, 223-232. doi:10.1016/j.sbspro.2012.09.649

APPENDIX A

MEEN 321 Survey

1. What is your sex?
   a. Male b. Female c. Prefer not to respond

2. What is your race?
   a. White b. African American c. American Indian or Alaska Native d. Asian e. Native Hawaiian or Other Pacific Islander

3. What is your major?

4. When struggling with an aspect of the project, what did you tend to do?
   a. Reach out to professor b. Reach out to classmates c. Reach out to past students d. Google solutions e. Other
   If other is selected, please explain what you do.

5. In general, how do you tend to solve problems when they arise in class projects?

6. What aspect of the project was the most difficult? Why?

7. What aspect of the project was the easiest? Why?

8. How could the instructions for the project be clearer and easier to understand?

9. What resources do you wish you would have had when completing this project?

10. Would you do anything differently if allowed to start the project over? If so, what?

11. How confident did you feel working on this project on your own?
    Not confident at all 1 2 3 4 5 Highly confident

12. Were the instructions clear for you to work on the project on your own?
    Yes No

13. Do you have any suggestions for this class?

14. If you could talk to someone about your project experience before they start the project, what would you tell them?

APPENDIX B

MEEN 321 Survey

1. What is your sex?
   a. Male b. Female c. Prefer not to respond

2. What is your race?
   a. White b. African American c. American Indian or Alaska Native d. Asian e. Native Hawaiian or Other Pacific Islander

3. What is your major?

4. When struggling with an aspect of the project, what did you tend to do?
   Reach out to professor b. Reach out to classmates c. Reach out to past students d. Google solutions e. Other
   If other is selected, please explain what you do.

5. How confident were you that you could solve problems when they arise?
   Extremely Confident
   Very Confident
   Moderately Confident
   Slightly Confident
   Not at all Confident

6. What aspect of the project was the most difficult? Why?

7. What aspect of the project was the easiest? Why?

8. How could the instructions for the project be clearer and easier to understand?

9. What resources do you wish you would have had when completing this project?

10. Would you do anything differently if allowed to start the project over? If so, what?

11. How confident did you feel working on this project on your own?
    Extremely Confident
    Very Confident
    Moderately Confident
    Slightly Confident
    Not at all Confident

12. How clear were the instructions for you to be able to work on your own?
    Extremely Clear
    Very Clear
    Moderately Clear
    Slightly Clear
    Not at all Clear

13. Do you have any suggestions for this class?

14. If you could talk to someone about your project experience before they start the project, what would you tell them?

APPENDIX C

Interview Questions

1. What is your gender?

2. What is your race?

3. Looking back on the plotter project, have you used any of the skills you learned in other classes or life? If so, which skills?

4. Do you feel that you will use any of the skills you learned in a future job? If so, which skills?

5. How confident are you on using the skills you learned from the class?
   Extremely Confident
   Very Confident
   Moderately Confident
   Slightly Confident
   Not at all Confident

6. How would you change the project now to better suite the skills you need to do well in your engineering classes as well as your future career?

7. How confident are you that you will be able to do well in an engineering career now having taken the MEEN 321 course?
   Extremely Confident
   Very Confident
   Moderately Confident
   Slightly Confident
   Not at all Confident

8. How confident are you with your problem solving skills now having taken this course?
   Extremely Confident
   Very Confident
   Moderately Confident
   Slightly Confident
   Not at all Confident

9. Is there anything else you would like me to know to make the project better?