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EXPLORING THE EFFECTS OF A PROBLEM TYPOLOGY FRAMEWORK ON STUDENT ENGAGEMENT IN A SELECTION PROBLEM

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ABSTRACT

In most engineering curricula, students are often not given opportunities to solve design problems outside their introductory engineering courses and capstone design. This inhibits them from exercising their ability to navigate ill-structured and complex problem elements inherent to design problems. Problem-based learning (PBL) can help provide opportunities to exercise these abilities by allowing students to gain experience in problem framing and decision-making. However, implementing PBL is often challenging because faculty must navigate problem design, facilitation, and assessment. In this study, we investigate the impact of using an explicit problem typology framework in facilitating student progression in a PBL environment where they engage with a selection problem, a common subproblem in design. One student section was exposed to this problem typology framework (intervention group), while another section was not (control). Using retrospective interview data from students, we analyzed how students talked about their engagement with the selection problem. Results of interview analysis were supplemented by analysis of student assignment submissions. We find that students introduced to the problem typology framework focused less on the reporting of equations and calculations, were more articulate in developing and describing the use of a ranking system in support of selection, and focused on aspects of mathematical and procedural reasoning contributing to the confidence in their final solution. Our interpretation of these findings is that students who used the framework began to view design as sociotechnical, not technorational, in nature. These facets may be missed, even in more open pedagogies like PBL, if facilitation strategies are not carefully considered. We believe these findings lend support for continuing efforts to operationalize Jonassen's design theory of problem solving to develop PBL environments.

Keywords: Selection, Problem-Based Learning, Problem Typology Framework

1. INTRODUCTION

Throughout their engineering education, students will be asked to solve different types of problems in a wide array of courses. These problem-solving activities are assigned with the intent of developing them into better problem-solvers who are equipped to design solutions to society's challenges. Engineers will be expected to both frame problems and make decisions that focus on moving the problem forward while engaging with others to exchange ideas and possible solutions. Such problems will be characterized by their complexity and ill-structuredness.

David Jonassen describes how ill-structured problems may have multiple solutions and solution paths, fewer defined parameters, and uncertainty surrounding the final solution and the processes used to arrive at a solution [1]. Conversely, well-structured problems have well-defined parameters and an apparent solution [1]. Jonassen identified 11 types of problems [2], noting that for engineering professionals the most common problem types encountered include selection, troubleshooting, and design problems [3,4]. In this study, we focus on the problem type of selection because of its direct tie to design decision-making. Students need to be familiar with how to navigate decision-making in engineering design, especially since they do not experience much design coursework in their middle years of engineering programs [5].

Problem-based learning (PBL) courses allow students to engage with complex and ill-structured problems so that they can further develop their problem-solving skills. This stands in opposition to repeating a standardized process, which is often a characterization of well-structured problems. However, there are limited resources that help engineering educators implement PBL experiences. The results presented in this paper are part of a larger investigation into how engineering educators can be supported in designing problems for, facilitating student engagement with, and assessing the outcomes of PBL.

In the area of PBL facilitation, there are many open questions about how educational advances can support student engagement with problems and student-teacher interactions. This paper explores the impact of a PBL intervention that is grounded in Jonassen's ideas of characterizing problems using problem typologies and for characterizing a problem's difficulty using the dimensions of structuredness and complexity. Specifically, we build on the work of one of the co-authors who has created problem typology frameworks for the common types of engineering problems [6,7]. By providing students with a typology framework as they engage with an ill-structured and complex problem, our hypothesis is that students will be more effective at framing aspects of the problem and will make connections between the problem aspects more effectively than students who are not introduced to an explicit framework.

In this exploratory study, we are motivated by the following question: *What impact does exposure to a problem typology framework for a selection problem have on student's problem-solving processes, thinking, outcomes, and decisions compared to students who were not exposed to such a framework?*

2. BACKGROUND

2.1. Selection in engineering design

An increasing number of internationally renowned engineering education certification institutions and organizations have proposed engineering design/application capabilities. The American discipline certification authority ABET (Accreditation Board for Engineering and Technology) revised eight standards to be implemented in the 2019–2020 certification cycle to further explain and define engineering design capability [8]. Design, a core competency in engineering, is defined as an iterative process drawing on content knowledge, engineering skills, and reasoned judgment. In professional practice, engineers are often presented with design problems from management, clients, and product users, and must then identify the problem to address when searching for solutions [9]. Engineering design problems are often characterized as complicated and ill-defined, standing in contrast to traditional textbook end-of-chapter problems. Arriving at effective solutions requires that designers take care to frame the problem (i.e., define the goals, criteria, and constraints) while responding to the dynamic nature of the problem's boundaries [2,10].

Design is an iterative process of making decisions about both the framing and solving of the problem; a co-evolutionary process [11] that integrates a series of decisions [12]. Successful solutions require that engineers successfully implement idea generation, development, and selection practices [13]. The identification of decision criteria and rationale (e.g., weighting of criteria) that governs the selection process is important. Identification of criteria and deliberation regarding their individual importance is representative of sociotechnical facets of design problems (i.e., design problems often contend with multiple conflicting objectives and non-technical criteria) [3,4].

During selection, engineers evaluate numerous ideas and select promising ones [14]. Recommended practices encourage designers to appropriately evaluate and select ideas by balancing benefits and trade-offs [15]. Various formalized methods have been developed, including the Analytical Hierarchy Process, Pugh's evaluation method, and Utility Theory. These methods assign attribute values to compare the characteristics of design options to find an optimal solution [13,16].

Lee et al. [13] explored student practices in idea generation, development, and selection through think-aloud experimental sessions and post-session interviews. Data analysis from mechanical engineering students' sessions incorporating think-aloud and interview data, revealed patterns of focusing on existing ideas, assuming constraining requirements, limiting idea development, and minimal engagement in idea selection. In the students' natural process of idea selection, they tended to focus on developing a single concept rather than comparing various ideas. Those who did consider multiple concepts relied on intuition and eventually selected a favorite idea. These behaviors are consistent with an approach to problem solving that seeks single, "right" answers and may be conditioned by a reliance on well-structured problem solving [4]. A learning intervention designed to disrupt these novice design behaviors led students to articulate important criteria and balanced benefits and trade-offs in selecting their idea [13], which are important characteristics of "informed designers" [15].

2.2. PBL

There have been tremendous efforts over the past two decades focused on the first year and final year of engineering education. First-year engineering students have been provided with opportunities to make sense of what engineering is, and what engineering design entails, for retention and motivation reasons. In their final year, the capstone design course imparts a synthesis experience, requiring that students apply much of their prior learning to solving complex, real-world design problems. The second and third years of engineering curriculums fail to offer students many opportunities to engage in engineering design processes and projects. It is essential to reconsider the learning objectives for the middle years of engineering education and explore innovative methods to incorporate engineering design into the curriculum [5].

Problem-based learning (PBL) has been proposed as an important instructional tool for engineering design. Assessment of PBL implementations has demonstrated improved knowledge retention, student satisfaction, and diversity in class and student learning [17]. PBL is a learning approach that confronts students with "an open-ended, ill structured, authentic (real-world) problem" where students work together to construct knowledge in developing a solution and instructors facilitate knowledge construction and solution development [18]. It is considered one of the more effective ways for students to learn design by experiencing design as active participants [19]. This engages them in the learning process, improves their problem-solving capabilities, and shifts the focus from regurgitation [20]. Overall, PBL has been found to have a generally positive impact on student learning of core knowledge and complementary skills (e.g., problem-solving) aligned with the profession, and supporting student learning in ways that lay "the foundations for a lifetime of continuing education" [21–25].

PBL approaches recognize that understanding a problem, and the way to approach different problem types, becomes central to fostering transformative learning and learning for the transformation of societies. Problems are the core of the learning process, and as students are the main players in solving these problems, it is important that they get the opportunity to identify, analyze, and solve problems. Problem design should be an integral part of engineering education [26]. PBL environments lend themselves to more constructivist approaches to learning, and this knowledge building is consistent with the nature of selection and design problems engaged in practice.

3. RESEARCH METHODOLOGY

This research is primarily qualitative in nature, deploying cognitive anthropology design-based research methodology [27] which links ethnographic methods to design-based research methods to characterize the experiences of students who are engaged in PBL for the first time. In this section, we describe the educational context and content, research participants, data, and analysis process. We analyzed retrospective student interviews and final assignment submissions where we applied In Vivo and axial coding processes. The remainder of the methodology section is structured as follows. In Section 3.1 we provide information about the differences in class structure between the two sections, A and B. Group A received the explicit introduction to a problem typology framework, while Group B does not. In Section 3.2, we provide further details about the student's participation in the study. In Section 3.3, we discuss the coding procedure used for the different data sources and provide further context for each.

3.1. Context and Content

The data used in this study was collected from an Intro to Aerospace Engineering course at a major research institution taught by one of the authors. The course occurs in the second year of the undergraduate aerospace engineering curriculum and is one of the first aerospace courses students experience. The course objective is to act as an introduction for students to the aerospace engineering discipline and provide context for other courses in the aerospace curriculum. It is offered as a one credit hour course, with students enrolling in one of two sections: referred to in this paper as Groups A and B. The goal was to introduce students to three types of problems that engineers face.

The problems designed for, and used in, both sections were described as either single-week problems or multi-week problems. Single-week problems introduced students to the fundamental nature of each problem type. Students received a single-week problem before they came to class. Before coming to class, students were asked to complete an online questionnaire about the problem. In class, students worked in groups to engage with this single week problem. At multiple times during the class period, the instructor would engage the class in discussion around navigating this type of engineering problem.

Multi-week problems allow the students to further engage with a new problem over multiple class periods. Here, they could focus on resolving the ill-structured and complex nature of the problem that a single-week problem did not allow. Both single- and multi-week problems were completed in groups of three students. Groups would remain the same for single- and multi-week problems, but students would receive new teammates when a new problem type was introduced.

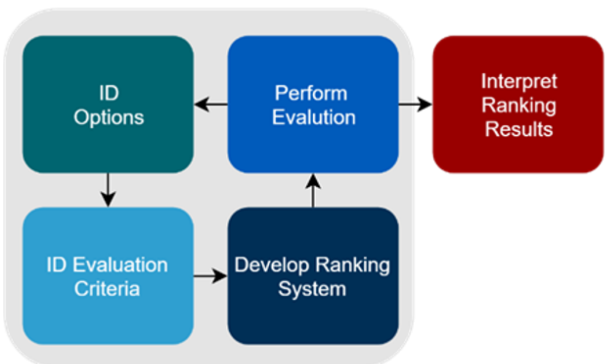
Prior to receiving the multi-week selection problem statement, students completed a single-week selection problem that focused on the steps of how a selection problem should be framed. This single week problem required the selection of an airfoil for an aircraft wing. They were expected to gather data about airfoil options, identify the criteria they wanted to use for making their final selection, and implement a ranking system.

The full problem statement for the multi-week problem, and the problem timeline and deliverables, are included in Appendix A.1. As mentioned previously, the multi-week problem this paper focuses on is a selection problem. The objective of this problem is to select a parachute that will be used to control the descent of a payload, ensuring that it meets the requirements outlined in the problem statement. Both the single- and multi-week selection problems expected the students to explain both the rationale and selection process they employed.

3.1.1. Group A and Problem Typology Framework

The typology framework presented in Figure 1 acts as a framework students can use during problem framing and solving while supporting discussion about different problem elements [28]. This framework was only shown to students in Group A, known as the experimental group, and the instructor framed the single-week problem discussion around each element. Students were also provided a PowerPoint presentation template to use for their milestone submissions. The template contained a slide corresponding to each box of the problem typology to encourage uniform submission following the framework. Throughout the multi-week selection problem, students were encouraged to develop a mental model of the selection problem, think of each stage of the typology, and consider the objective and how they could engage with the problem.

My mental model for this problem is that it is an engineering selection problem. It has five stages.



Objective: Identify the best option from a set of options by considering multiple criteria. Problem engagement involves considering benefits and limitations, weighting options, and justifying your selection.

Figure 1: PROBLEM TYPOLOGY FRAMEWORK SHOWN IN GROUP A

Additionally, each box of the problem typology has a set of questions associated with it, as listed in Table 1. These questions demonstrate that there are decisions students need to make at all stages of the problem.

TABLE 1: QUESTIONS ASSOCIATED WITH EACH LEVEL OF THE PROBLEM TYPOLOGY FRAMEWORK.

Stage	Associated questions
ID Options	• What choices are available? • What do I know about them? • What information do I need to find?
ID Evaluation Criteria	• What are my assessment criteria? • How many should I consider? • Preference direction for each criteria? (bigger is better, smaller is better, etc.)
Develop Ranking System	• How do I represent the difference between options for each criteria? • How important is each criteria? • How do I represent this thought process?
Perform Evaluation	• Conducting concept “scoring” • Identification of best option
Interpret Ranking Results	• Do I agree with my own outcome? • Are there clear non-contenders? • Conduct sensitivity/uncertainty analysis?

The problem typology is intended to be an abstraction of the decision-making process, framing its respective steps. The typology can be thought of as a type of guardrail that allows the students to consider the judgment they are making with respect to each individual box.

3.1.2. Group B and Headings

The students in Group B were not shown the problem typology framework. They acted as a control group and were given a slide template with the headings and order of each slide. The bullet points in Table 2 list the general steps of decision-making that were given to students to organize their assignment submissions for both the single- and multi-week selection problems. The instructor engaged students in Group B by facilitating the single and multi-week problems and discussion around each bullet point listed in Table 2. This ensured that both groups received facilitation, with the primary difference being the presence of the problem typology framework. An overview of this methodology can be observed in Figure 2.

TABLE 2: SLIDE HEADINGS PROVIDED TO GROUP B FOR SINGLE- AND MULTI-WEEK SELECTION PROBLEMS SUBMISSION TEMPLATES.

Slide headings for single-week selection problem
• Describe the decision • Describe the information you know about your alternatives • Describe the rationale you used for making a choice • Report the final decision
Slide headings for multi-week selection problem
• Describe the decision • Option identification • Describe the information you know about your alternatives • Describe the criteria that you will use for assessing the options • Assess your options on the criteria that you have defined • Describe the rationale you used for making a choice • Report and assess the final decision

3.2. Participants

The participants were students with sophomore-year standing in the aerospace engineering program. This is a required class. Based on our observations and interactions with the students, these students have largely either never experienced a PBL style classroom or participated in a research project before.

Interviews were conducted with students who consented to participate in the research process. On the first day of class, a PI other than the instructor informed the students that they may opt in to participate in retrospective interviews, giving them the opportunity to describe their experience in solving various problems throughout the semester. Additionally, only one interview occurred and was completed after the class section had finished the problem. Students submitted three assignment submissions throughout the course of the problem: checkpoint 1, checkpoint 2, and a final submission. For the purposes of this

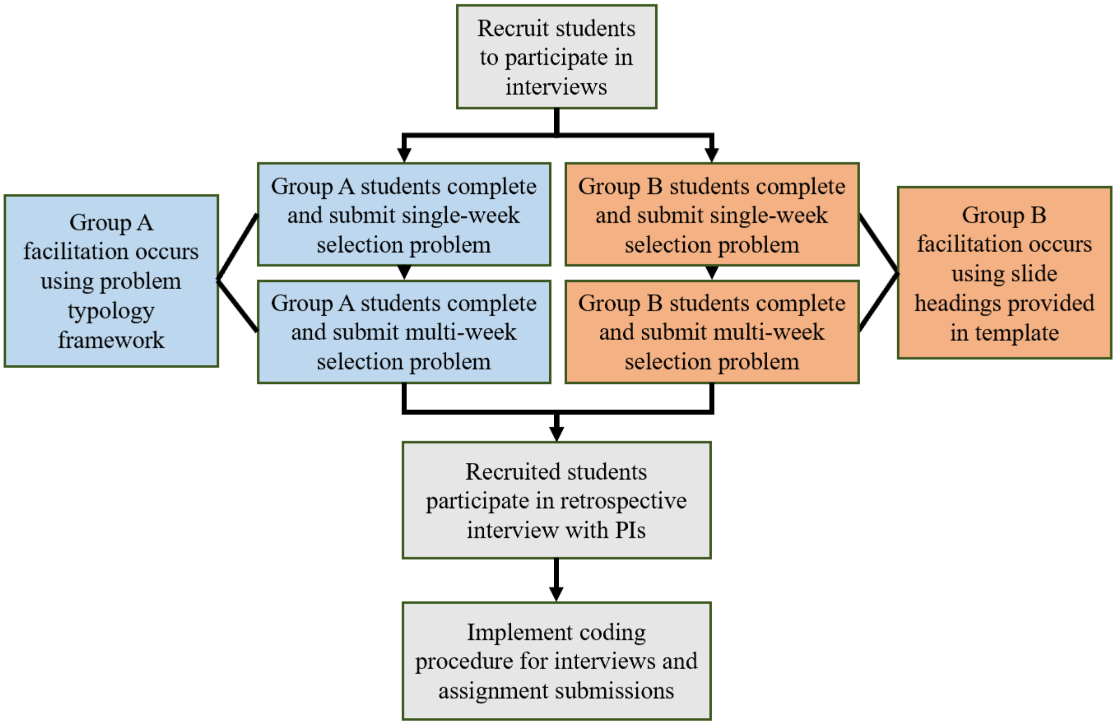


FIGURE 2: OVERVIEW OF METHODOLOGY.

study, only the final submission was analyzed. Participant identities were protected through secure data collection and storage. Pseudonyms were assigned to each interviewee. To avoid students feeling pressure to participate, or inducing worry that their grades could be compromised, it was unbeknownst to the instructor which students were participating in the research. Each participant was compensated $10 for each interview. IRB protocol was adhered to during each step of the research process.

We initially recruited 10 students for both Groups A and B from each section (each section had approximately 60 students). However, some students dropped out of the study due to other time commitments or they no longer wished to participate. New students could not be recruited quickly enough to replace them. The final breakdown of participants was six students in Group A and ten students in Group B.

3.3. Coding procedure

Coding methodologies were applied to interview transcripts and student assignment submissions (PowerPoint slide PDF files). Dedoose [29] was used for the coding of data and subsequent analysis. While coding, researchers memoed initial observations from all data sources. We discuss the specific coding methodologies for each type of data set below. The final code lists used are available upon request.

3.3.1. Interviews

Interviews for the multi-week selection problem were completed between each student and the research team (not the instructor) after the multi-week selection problem assignment deadline. The interviews followed a set of pre-determined questions, listed in Table A.2 in the appendix. Recorded interviews were conducted via Zoom with each participant. The automatic transcript was downloaded, and a researcher re-watched the interview to ensure that the transcription was accurate prior to uploading to Dedoose. The coding process used for the interviews is represented in Figure 3. The first cycle of coding was completed using the In Vivo coding process outlined by Saldana [30] where codes were generated “verbatim”. Since we are most interested in understanding the experience of the student solving problems in a PBL environment, In Vivo coding was determined to be an appropriate choice. Each question the interviewer asked was coded as a parent code, and child codes emerged from students’ responses. To begin second cycle coding, focused coding was applied and allowed for major categories to develop within the code list for each question.

Finally, an axial coding process was completed during the second coding cycle to remove redundant codes, reorganize existing codes, and further develop categories and subcategories within the code list [30]. This process was completed by two graduate researchers who had previous qualitative coding experience. They completed the axial coding process together for two questions to ensure they were in agreement prior to dividing the remainder of the questions. After individually completing their respective questions, they then discussed the codes associated with each question to further ensure agreement.

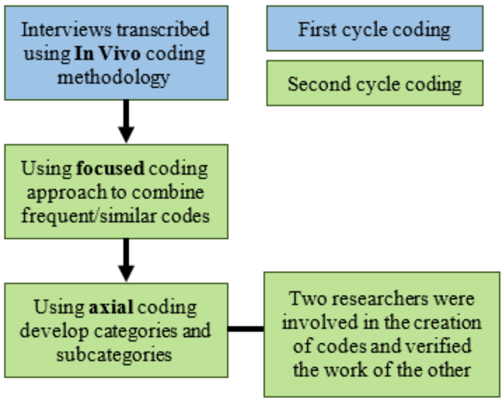


FIGURE 3: PROCEDURE FOLLOWED DURING CODING OF INTERVIEWS.

During the second-cycle coding process, major themes for each interview question were developed and these became the basis for further analysis. An example of the codes for an interview question is provided in Table 3 and the thematic categories are highlighted. It should be noted that the child codes listed below are not representative of the whole list and other questions may have thematic categories that vary slightly from below. We explore specific thematic categories of interest in the following sections of the analysis.

TABLE 3: EXAMPLE OF CHILD CODES AS MAJOR THEMES.

Q: Where did you start?

- Considering parachutes
  - Find parachutes that fit payload bay
  - Exclude parachute options
  - Look at different parachute options
- Considering variables
  - Kinetic energy
  - Impact energy
  - Descent rate
- Concentration on equations/calculations
  - Find equations
  - Crunching numbers, getting ranges
  - Calculate velocity and time
- Procedural/problem solving
  - FruityChutes
  - Asking what knowns/unknowns are
  - Divided up parts of flight
- Self-efficacy
  - Had trouble understanding phases of flight
  - Know what scope of problem is
  - Understanding what variables mean and how they impact the problem

3.3.2. Assignment submissions

The collected data also consists of student assignment submissions. The PowerPoint assignment submissions for Group A followed the five stages associated with the selection problem outlined in the problem typology. These five stages acted as parent codes and child codes emerged from the slides' content. If students added any slides with headings that were not one of the five stages in the problem typology, a new parent code was assigned but was done so outside of the problem typology parent code to not appear as being part of the problem typology.

A similar process was followed for the Group B assignment submissions where the heading given on the slide template was a parent code and information on the slide was a child code. New parent codes were assigned for any slides that were not categorized under one of the slide headings.

4. ANALYSIS

Our analysis focuses on student interview responses, specifically how students talked about their engagement with the problem. We then analyze the assignment submissions as part of the triangulation process. The combination of interview data and assignment submission analysis provides a more comprehensive understanding of the students' experiences, actions, and helps with data triangulation. Since the groups did not have an even number of students who opted to participate in the interview process, we supplement this gap with additional student assignment submissions from students who were not part of the interview process. We looked at 10 submissions for each group. Our analysis identified three major themes of interest: ranking system articulation, concentration on equations and calculations, and confidence reasoning.

4.1. Theme 1 – Ranking System Articulation and Justification

To assess the areas where students encountered difficulty in the problem, we examined the questions "What was the most difficult aspect of solving the problem" and "Was there anything about the process or procedure that was difficult?". Students identified various aspects of the problem as challenging when solving the problem. However, we emphasize a specific aspect of this selection problem where students encountered difficulty, the implementation of the ranking system, as shown in Table 4.

TABLE 4: FREQUENCY OF EACH CODE AMONG GROUPS A AND B FOR Q: WHAT WAS THE MOST DIFFICULT ASPECT OF SOLVING THIS PROBLEM? & Q: WAS THERE ANYTHING ABOUT THE PROCESS OR PROCEDURE THAT WAS DIFFICULT – RANKING SYSTEM PARENT CODE.

Child code	Group A	Group B
Number of students who mentioned each code	3/6	2/10
Optimizing	1	
Ranking similar parachutes	1	
Weighting of ranking system	1	
Ranking system weighting importance	1	1
Different weights give different results	1	
Took time to get ranking system set up so it wasn't inaccurate		1
Total occurrence of code	5	2

Additionally, as reported in Table 5, we counted the number of words students used in their assignment submissions to justify their weights and criteria used for their ranking system.

TABLE 5: NUMBER OF WORDS USED TO JUSTIFY WEIGHTS IN RANKING SYSTEM.

Group A No.	Number of Words	Group B No.	Number of Words
01	107	01	38
02	45	02	98
03	114	05	68
04	112	08	14
05	49	09	60
07	35	10	100
08	123	11	12
11	32	12	162
15	118	15	38
18	37	16	22
Mean	77.2	**Mean**	61.2
St dev	38.1	**St dev**	45.1

4.2. Theme 2 – Concentration on Equations and Calculations

We are interested how the presence of a problem typology framework impacts student engagement and progression with a problem. We focus on the themes pertaining to equations and calculations to understand how students made use of equations and calculations to make progress in solving the problem and the role they had in making a selection.

We examined each interview question that had a theme of concentration on equations and calculations, and assessed the frequency of assigned codes for both Groups A and B. We began with the question, "What are the major steps in the process that you used to solve the problem?" and looked at the child codes that stem from the Concentration on Equations/Calculations parent code. The frequency of coded responses and the number of students who mentioned the code are reported in Table 6.

TABLE 6: FREQUENCY OF EACH CODE AMONG GROUPS A AND B FOR Q: WHAT ARE THE MAJOR STEPS IN THE PROCESS THAT YOU USED TO SOLVE THE PROBLEM?

Child code	Group A	Group B
Number of students who mentioned each code	1/6	4/10
Created bounds for calcs	1	
Calcs help to know if parachute is feasible	1	
Calcs to find time/velocity between each step		1
Code for calculations		1
Apply drift equations to parachutes		1
Determining detail for models		1
Finding equations		1
Research for calculations		1
Total occurrence of code	2	6

Next, we assessed the question, "What did you need to know to solve this problem? How did you acquire that knowledge?". The frequency of assigned child codes is shown in Table 7. We then examined student responses to the question, "What was the most difficult aspect of solving this problem?" as shown in Table 8. Finally, we compared the number of equations that students used in their assignment submissions, as reported in Table 9.

TABLE 7: FREQUENCY OF EACH CODE AMONG GROUPS A AND B FOR Q: WHAT DID YOU NEED TO KNOW TO SOLVE THIS PROBLEM? HOW DID YOU ACQUIRE THAT KNOWLEDGE?

Child code	Group A	Group B
Number of students who mentioned each code	4/6	9/10
Concentration on equations/calculations	1	
Falling equations		1
Drag	1	2
Drift distances/equations	2	2
Equations from previous/current class	2	3
MAE 251 (AVP)	2	1
Physics class	1	
Statics		1
Calcs for parachutes		1
How to calculate things		1
Kinematic equations		7
Applying to each step of process		1
Plug and chug		1
Unit conversion		1
Total occurrence of code	9	22

TABLE 8: FREQUENCY OF EACH CODE AMONG GROUPS A AND B FOR Q: WHAT WAS THE MOST DIFFICULT ASPECT OF SOLVING THIS PROBLEM?

Child code	Group A	Group B
Number of students who mentioned each code	1/6	5/10
Calculations/equations		
Terminal velocity calculations		2
Physics and the math		1
Flew through after physics was done		1
How to get calculations done	1	
Figuring out which equations to use	1	
Using equations		2
Wind drift calculations		1
Total occurrence of code	2	7

TABLE 9: NUMBER OF EQUATIONS PER STUDENT ASSIGNMENT SUBMISSION.

Group A No.	Number of Equations	Group B No.	Number of Equations
01	0	01	4
02	0	02	13
03	0	05	19
04	5	08	0
05	7	09	0
07	1	10	3
08	2	11	5
11	0	12	24
15	5	15	6
18	10	16	11
Mean	3	**Mean**	8.5
St dev	3.38	**St dev**	7.68

4.3. Theme 3 – Confidence in Solution Reasoning

We seek to assess how students reasoned their confidence in their final solution and understand their justification by focusing on mathematical and procedural reasoning. We examined the question, "Why are you confident about your solution?" and extracted major themes from student responses. The child code breakdown, and number of students who were coded to each mathematical reasoning child code is shown in Table 10. We report the child code breakdown, and the number of students coded to each procedural reasoning child code in Table 11.

TABLE 10: FREQUENCY OF EACH CODE AMONG GROUPS A AND B FOR Q: WHY ARE YOU CONFIDENT ABOUT YOUR SOLUTION? – MATHEMATICAL REASONING CODE.

Child code	Group A	Group B
Number of students who mentioned each code	3/6	5/10
Feels approximations did not compromise accuracy		1
Confident about physics		2
Confident in modeling they equations		3
Equations computed in FruityChutes		1
Found equations/values easily		1
Model still worked even though changed coef. of drag assumption		1
Confident in the numbers/math	1	
Confidence of being in right ballpark	1	
Feels models are accurate		1
Math agreed with logic	1	
Solution logically made sense	1	
Total occurrence of code	4	10

Table 11: FREQUENCY OF EACH CODE AMONG GROUPS A AND B FOR Q: WHY ARE YOU CONFIDENT ABOUT YOUR SOLUTION? – PROCEDURAL REASONING CODE.

Child code	Group A	Group B
Number of students who mentioned each code	1/6	4/10
More focus on ranking than one right answer	1	
Checked work		1
Easy to determine optimal parachute		1
Hard to mess up problem		1
Binary yes or no decision, work or it won't		1
Not as numerical	1	
Not too many ways to deviate from solution		1
Way they analyzed and factors considered		1
Went through steps to succeed		1
Total occurrence of code	2	7

5. RESULTS

For each major theme identified, we comment on the observations from the interview data tables. We then discuss observations from the assignment submissions to enhance data triangulation.

5.1. Theme 1 – Ranking System Articulation and Justification

First, we assess how students interacted with a particular facet of the selection problem: the ranking system. Group A's problem framing was centered around a ranking system as it was explicitly stated in the problem typology framework. The questions associated with ranking, shown in Table 1, directed their problem-solving strategy around ranking, option identification, and assessment criteria. The use of the ranking system is where students in Group A identified the most difficulty in the problem. Half of the students mentioned difficulty using a ranking system, as shown in Table 4, while only 2/10 students in Group B referenced this. The correlating step for Group B was listed as "assess your options on the criteria that you have defined". There was no mention of using a ranking system. When comparing the assignment submissions for both Groups A and B, however, every student group used a ranking table. This is likely because a ranking system was discussed during the single-lecture selection problem.

When considering the assignment submissions, we examined the slides about 'developing a ranking system' and 'assessing the options on the criteria that have been defined'. A main difference between the two groups was whether they provided any explanation or justification for their chosen ranking system weights. The word count provided by each group is reported in Table 5. Initially, it appeared that Group B provided less detail in their justification for weight assignment. However, a statistical analysis of the data revealed that the difference in word count between the two groups was not statistically significant. The mean word count for Groups A and B were 77.2 and 61.2, respectively with a standard deviation for Groups A and B being 38.1 and 45.1, respectively. Additional analysis into differences between the Group A and B artifacts is the subject of future work, and further consideration about what constitutes justification of criteria will be required since some groups chose to restate the problem requirements as their justification.

Many students reported that they had never formally used a ranking system. When asked during the interviews if they had ever used a ranking process before, one interviewee responded:

"Um, not probably like intentionally. I'm sure like internally in my head, …, or like kind of what I was saying, like we knew already in our head that like impact energy was better, like [that] was something that we wanted to prioritize. So like in our heads, I think we were doing it subconsciously, but like we hadn't, it's not really something I'd ever like written down and like done formally. Probably not." [emphasis ours]

The concept of practically implementing the ranking system was new to the students. The student quoted above indicated that the act of selecting is usually done as an internal mental process. Students in Group A experienced difficulty in framing aspects of the ranking system when they were explicitly stated as elements of the problem typology framework.

As educators, we want to provide students with experiences that equip them to make informed design decisions, provide a process for a course of action, and aid in confidence. However, the Group A students reporting difficulty with framing the ranking system leads us to consider the degree to which the problem typology framework could become overly prescriptive. The framework is meant to act as a tool that students can employ to help them make progress with the problem and exercise their engineering judgement. However, if the framework is viewed as a prescriptive process, students may use it to replace their exercising of judgement.

5.2. Theme 2 – Concentration on Equations and Calculations

We observed that Group B, who did not see the problem typology framework, referenced the use of equations or calculations more frequently than Group A, as reported in Table 6. Interviewees in Group B stated that some of the major steps used to solve the problem included finding equations and doing research to be used for their calculations. Additionally, only one student in Group A referenced using equations as a major step in the problem, whereas 4/10 students did so in Group B.

We also see an increased number of codes assigned to students in Group B that are focused on looking for calculations applicable to parachutes. Group B students also mentioned the use of kinematic equations, as shown in Table 7. No students in Group A mentioned kinematic equations in their interviews.

From the code list reported in Table 8 we observe that half of the Group B students found doing calculations for specific variables to be challenging. They also reported difficulty around using the equations and completing the math associated with those equations. Students in Group A identified the difficult part of the problem to be the ranking system. There is the possibility that students in Group B had an increased reliance on using equations and calculations in their problem-solving process. Without an explicit problem typology framework to follow, the Group B students may have spent more time in these areas and focused their problem-solving efforts around equations.

We compare these observations from the interviews with those of the assignment submissions to assess if similar behavior occurred. When comparing the number of equations in Group A's submissions, we observed that they do include and show the equations used. However, they do so less frequently than Group B, as shown in Table 9. While there were some groups that did not include any equations in their final submission slides, most Group B submissions reported a larger number of equations.

We also observed a difference in the format of equation presentation. Students in Group A opted to type their equations into their slides and used more structure in equation formatting. Group B, conversely, included pictures of handwritten pencil and paper equations and calculations. We question if this difference can be attributed to the problem typology framework that provided Group A students with a more thorough understanding of what types of calculations were necessary to make progress in the problem and what should be included in their submissions. This remains unknown but should be considered in future work.

We supplement these observations with a quote from a student in Group A. They explained how they learned from the process used in a previous problem introduced in the course. That problem had a larger number of calculations, as it focused on analysis. They felt as if they were making better procedural decisions regarding calculations:

"The last [problem] we probably kind of tried to focus a bunch on calculations and trying to figure out exact details. But we kind of realized at the very end that that wasn't really necessary. And so we were able to apply that kind of learning and knowledge to this problem, where we saw a bunch of numbers, and we immediately didn't go into making calculations. We kind of took a step back and said, ok, we have these numbers, but we're looking for a very specific thing. So what do we really need from these numbers versus just jumping straight in and calculating everything possible that we can about it." [emphasis ours]

This quote demonstrates the impact a problem typology framework can have on student experience. Rather than immediately beginning with calculations, the student saw value in considering more specific elements of the problem. They then proceeded forward with calculations intentionally. The introduction, and use of the framework, altered their approach and their thought process seemed to also change.

5.3. Theme 3 – Confidence in Solution Reasoning

The reasoning students provide for their confidence allows us to gain deeper insight into their interaction with the problem and consider how they navigate the design process.

5.3.1. Mathematical Reasoning

Each group had half of the students use mathematical reasoning to justify their confidence in their final decision, as shown in Table 10. However, we see that Group A focused on a more holistic view of the problem with the codes assigned to their statements. One student indicated that their math agreed with the logic of the problem, and they felt their solution made sense. Another student was confident they were in the right ballpark with their solution.

This is quite different from the Group B statements. Those students felt confident because of their equations and calculations, ability to find equations, and calculations computed using the FruityChutes online calculator. As we further contrast the assigned codes, it appears that the codes associated with Group A link their confidence level to their outcome of the problem, whereas Group B's confidence is linked to the methods they used in solving. This leads us to question whether the problem typology framework allowed students in Group A to think more deeply about the problem and their final choice.

5.3.2. Procedural Reasoning

The one student from Group A that was assigned a procedural reasoning code, listed in Table 11, indicated that they felt more confident since this problem was more focused on using the ranking system than finding one correct answer. They also felt confident because it was less numerical. This is contrasted with a higher number of student responses from Group B who indicated they felt more confident because of the ease of finding parachutes, the problem not allowing for ways to deviate from the final solution, and their analysis of different factors. Group B also felt confident because they went through the steps they perceived to be required for success.

It is possible students succumbed to the false belief that if they followed a methodology, such as the one presented in the slide headings, success would be guaranteed. We further contrast these differences between Group A and B with a quote from each. When asked where the knowledge of using a ranking system came from, a student from Group A responded with an explanation of how the instructor emphasized the need for a detailed analysis:

"So over the past couple of classes he's been stressing to me that like you need to be able to quantify your evidence, you gotta be able to say that this is weighted this many points rather than just ranking it outright because that's not an effective way of structuring your ideas."

The student demonstrates their understanding of the importance of justifying decisions and making choices intentionally. This is contrasted with a student response from Group B explaining a major difference between the multi-week selection problem and a previous multi-week analysis problem. They refer to the multi-week selection problem and state that:

"We were like, not forced to think that much outside of the box to what would be a rational choice when making our calculations, so that made it a more straightforward process."

The student indicates their thinking followed a prescriptive mindset and implies they may not have considered the feasibility of their mathematical result. This is potentially problematic, especially when correlated with the tendency to rely on calculations and equations. Students must be able to critically reflect upon and question their results to fully understand if the choice they are making is the most ideal one.

5.3.3. Additional Observations About Reasoning

The assignment submissions revealed additional insights about the reasoning and justification students used in their final decision of selecting a parachute. While Section 5.3 concentrates on students providing reasoning to their level of confidence in their solution, we observed a difference in how students justified their final solution in the assignment submissions.

Part of the problem typology framework was to conduct a sensitivity/uncertainty analysis to assist in validating the outcome of the ranking system. Since Group A saw this element of the framework, they referenced other parachutes that ranked second or third and explained why they were not selected. Group B did not assess additional parachutes or conduct such an analysis. Rather, they selected the parachute that was the best outcome of ranking and did not provide additional discussion about why it was chosen. By not considering how their weights could change or completing an additional analysis, it is possible they could have ended up with a suboptimal selection.

5.4. Possible Impact of Problem Typology Framework

While performing data review, the researchers made note of a unique observation. This problem was the second multi-lecture problem given to the students. The first multi-week problem was a tradespace analysis problem. When the interviewer asked the question, "How does this problem [the multi-week selection problem] compare with the last one [the multi-week analysis problem]? What similarities and differences are there?", six out of the ten students in Group B would either ask for a reminder of the previous problem or stated they did not remember that problem. Conversely, there were zero students in Group A who asked for a reminder of the multi-week analysis problem.

This is a possible indication of the effect of the problem typology framework. Based on this finding and others from the above thematic sections, we suspect that the intervention of the problem typology framework has an impact on student problem-solving in that it may assist in removing some of the ill-structuredness and complexity from the problem. The slide headings shown to Group B did not have the same impact as the problem typology did for Group A; it may not have "stuck" in their minds the same way. However, it is necessary to consider to what extent the problem typology framework could become a prescriptive process and replace the student's exercising critical thinking and problem-solving skills. Further research is needed into how we should best structure processes that enable students to think with unbiased autonomy and have agency over the problem, yet still provide them with enough rigidity to not solely rely on their internal reasoning.

6. DISCUSSION

6.1. Design as Sociotechnical vs Technorational Problem Solving

We begin by discussing the theme of students concentrating on equations and calculations and how this potentially relates with the problem typology framework. We see that through their dependence on mathematical approaches, Group B demonstrates a technorational way of thinking. This potentially conflicts with processes used in engineering design by experts. In our thematic and coding analysis, we observed that students in Group B frequently referenced the use of kinematic equations. They are likely familiar with these equations through previous classes they have taken, such as physics. They also have likely used kinematics to solve many "plug and chug" types of problems. It is possible that 1) more students in Group B knew they needed to use these equations, 2) they resorted back to them since the equations evoke familiarity, or 3) that this problem reminded them of another problem where they had to use kinematic equations. Further inquiry is needed to validate this observation.

While Group A also used and mentioned equations in their submissions and interviews, they did so less than Group B. Most of the engineering classes focus on well-defined problems where problem procedures are centered around working with equations and doing calculations. For the students in Group A, the problem typology framework disrupted their technorational mindset, allowing them to foreground the problem as a bigger process.

We view this disruption of the technorational mindset as significant. There have been many efforts to make elements of design, particularly decision-making, a purely mathematical process. Yet, selection—which embodies the act of decision-making—may be an inherently social process where engineers cannot rely solely on equations and calculations. Engineering students must learn to assess the quality of their answer and determine if that answer is realistic and aligns with expectation. This assessment is better known as a sociotechnical approach.

In a sociotechnical approach, students are expected to engage with their peers and discuss problem elements to arrive at a consensus on what matters. Framing of the problem, as foregrounded by the problem typology framework, can assist in keeping the end goals in mind for the student and help them make decisions with the intention of moving the design process forward. This priming may prohibit students from putting their priorities on finding equations or arriving at numbers and circumventing this framing process. This study provides further insight into how students in Group A, who experienced a disruption in learning, may have framed the problem differently than those in Group B.

6.2. Limitations

A few limiting factors existed in this study, one being the sample size of student interviewees. This led to uneven groups between the sections and somewhat limited our analysis of the interview data. In data collected from the current academic year's course, we attempted to account for students withdrawing from the study by recruiting more interviewees at the start of the year. This strategy was successful as there now exists the same number of participants per section. An additional limitation was the interviews being retrospective. If students were actively working on the problems during the time the interviews occurred, for example, if we used think aloud protocols, they may have provided slightly different responses. However, we acknowledge there are certain limitations to these methods as well. An additional limitation we make note of is the difficulty of tracking each individual student's contributions in the assignment submissions. Even though students do explain the contributions of each team member, it is challenging to know the exact submission content the interviewee is responsible for. Thus, when we analyze assignment submissions, we are really assessing the group's work rather than just one student.

6.3. Future work

We plan on expanding this study by analyzing additional data from Fall 2023 course participants who were given the same selection problem, comparing their experiences with the students in this study. Additionally, we plan on employing a more rigorous analysis of assignment submissions. This will include using multiple researchers to mitigate bias in the coding of thematic elements. We also plan to analyze all assignment submissions. This allows us the opportunity to track the group's progress throughout the duration of the problem.

Additionally, we wonder whether using a problem typology framework for a different type of problem would yield similar results. We plan to also explore this by analyzing the multi-week analysis problem with data from both academic years.

Finally, we consider possible longitudinal studies that could occur in this research area. We are intrigued by the premise of students participating in a PBL type classroom for a course in the early years of their engineering curriculum and following up with them during their final year to evaluate if they used the processes learned in the PBL based course in their other courses. Finally, we wonder how students would navigate a PBL environment in another engineering class, such as thermodynamics or solid mechanics, and what effects this would have at different years of the curriculum.

7. CONCLUSION

In this study, we seek to understand how the use of a problem typology framework in a PBL style learning environment can assist students in their problem-solving process and how they make decisions in the engineering design process. We showed that using the problem typology framework may assist students in developing their judgment about what steps they must take to make progress in the problem. Students in Group A framed their approach to the problem around the ranking system but also reported it being difficult. This highlights how the problem typology framework influenced their thought process. The instructor could have given the students a more prescriptive approach to follow, but instead the students were given the freedom and agency to explore decision-making and attributes of a selection problem, such as how to weight their criteria and what the weights should be.

We also see the potential for students who do not have access to the problem typology framework to rely more on performing calculations and equations and centering their progress in the problem around them. Students in Group B took a more technorational approach to solving the problem and we consider the effects of this in design problems. There is a social aspect prevalent in decision-making since students are expected to work together and make informed decisions. The dangers of relying on a technorational approach potentially means that students may be completing different tasks without a full view of the problem. More investigation is required to further understand this idea of students using equations more dominantly throughout their work.

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APPENDIX

A.1. Introduction to Aerospace Engineering – Parachute Problem Statement

Your analysis on rocket motor engines helped the group ascertain that the engine they selected (F15-6) would not help the design reach the required apogee altitude. Changes were made to the rocket body and a different engine was subsequently chosen. During the sub-scale launch test, the group was able to reach the desired target altitude

Work has continued on making the full-scale launch vehicle for competition. This rocket will carry a 9 lb payload to a target apogee of 4800 ft. The current design of the payload is 22 inches in length. It must be placed within the Upper Payload Bay which is currently designed to be 24 inches in length. The weight of the rocket at launch is approximately 48.5 lbs. It takes the rocket approximately 19 seconds to reach apogee.

At apogee, the rocket will be at 43.1 lbs. Pyrotechnic charges are then detonated to separate the components of the rocket body and allow the deployment of a drogue parachute. The team typically purchases their parachutes from Fruity Chutes (https://fruitychutes.com/). The Recovery Lead has already specified that an 18-inch Classic Elliptical parachute will be the drogue chute. Information on this parachute is here: https://shop.fruitychutes.com/collections/classic-elliptical-12-to-60/products/18-elliptical-parachute-1-2-lb-20fps

At 700 feet above ground level (AGL), the forward pyrotechnic charge is triggered and the nosecone and payload bay are separated. This separation allows for the deployment of the main parachute and the deployment of the payload, as in Figure A1.

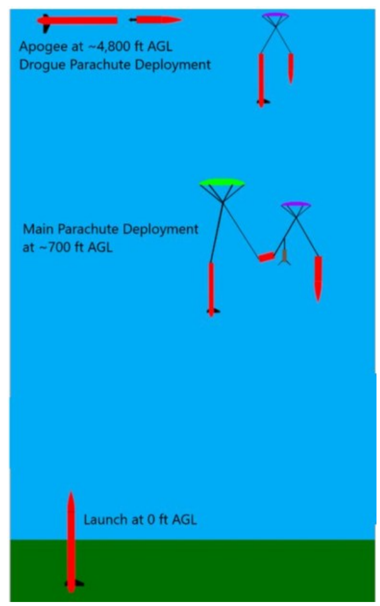

Figure A1: STAGES OF FLIGHT OF PARACHUTE AND PAYLOAD.

The payload immediately detaches from the main parachute harness and begins to free-fall. The payload will descent under a furled parachute in a Nomex deployment bag and is kept secured by a Jolly Logic Chute Release device (consisting of an altimeter and a latch). This device wraps around the furled parachute and deployment bag with an elastic band. At 300 ft above ground level, the Jolly Logic device will unlatch, allowing the parachute to unfurl. The payload continues to the ground and upon landing the payload parachute will be jettisoned.

Once on the ground, the team will send commands to the payload that control a camera. Multiple pictures will be taken and those images are then sent back to the team at the launch site.

Your task is selecting the parachute that will be used to control the descent of the payload. In documenting your choice, you must also explain the rationale and selection process used.

The following requirements from the NASA Student Launch Competition Handbook may influence aspects of your decision:

- Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.
- The recovery area will be limited to a 2,500 ft. radius from the launch pads.
- Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down).

They also require that teams calculate the drift for each section of the launch vehicle from the launch pad for five different cases: no wind, 5-mph wind, 10-mph wind, 15-mph wind, and 20-mph wind. The drift calculations should be performed with the assumption that apogee is reached directly above the launch pad.

<u>Problem timeline and deliverables</u>

- Multi lecture problem #2 pre-class reflection (due before class on 10/7)

- Checkpoint #1 (due by 11:55 pm eastern on 10/12)
  - One of your group members must submit a single PowerPoint deck to Moodle
  - This PowerPoint deck should include problem name and number, checkpoint number, date, names of students and an organized presentation of all artifacts (diagrams, sketches, models, calculations, etc.) that explain your solution process so far
  - Objective for this checkpoint: Describe the options that are available and evaluation criteria that you plan on using

- Checkpoint #2 (due by 11:55 pm eastern on 10/18)
  - One of your group members must submit a single PowerPoint deck to Moodle
  - Contents of the PowerPoint deck will build on your previous checkpoint submission
  - Objective for this checkpoint: Describe how you evaluate/score the options that you identified and conduct your evaluation

- Problem solution to Multi Lecture Problem #2 (due by 11:55 pm eastern on 10/25)
  - One of your group members must submit a single PowerPoint deck to Moodle
  - Contents of the PowerPoint deck will build on your previous checkpoint submission
  - Additional information to include is your final selection and an interpretation of your results o Also include a description of what each group member was responsible for

- Multi lecture problem #2 post-class reflection (due on 10/25)

A.2. Interview Questions

TABLE A.3.: INTERVIEW QUESTIONS.

Can you describe the problem in your own words?
What type of problem is this?
What are the major steps in the process that you used to solve the problem? Do you think you could draw this as a process? Can you do this and email it to me?
Where did you start? Why?
What did you need to know to solve this problem? How did you acquire that knowledge?
What was the most difficult aspect of solving this problem? Was there anything about the process or procedure that was difficult?
Was there any process or procedural knowledge you needed to know?
Where did you learn that procedure?
What were your criteria for making decisions?
How did you navigate the decision-making side of the problem?
How does this problem compare with the last one? What similarities and differences are there?
How did you and your group members collaborate on this problem? Why? How did you partition work?
Did you like the partitioning of work? Did you get to contribute in the ways that you wanted to?
How confident are you about your solution? Why? How do you know if you are correct?
If you got the same type of problem with a similar difficulty level in another class (e.g. Thermodynamics) are you more confident that you could solve or make progress after this experience? Why?
Did you get to contribute in the ways you wanted to?
Have you ever worked on a problem like this before? (Prior experience). Where does your knowledge for working on the problem come from? (Prior knowledge)
Was your understanding with this problem different than last time?