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Assessing the Impact of Engineering Problem Typology on Students' Initial Problem-solving Trajectory

Dr. Andrew Olewnik, University at Buffalo

Andrew Olewnik is an Assistant Professor in the Department of Engineering Education at the University at Buffalo. His research includes undergraduate engineering education with focus on engineering design process and methods, ill-structured problem solving, problem typology, and experiential and informal learning environments in the professional formation of engineers. He is interested in the development of tools, methods, and strategies that aid in engineering problem definition, and problem solving discourse among students, faculty, and practitioners. Dr. Olewnik is also the Director of Experiential Learning for the School of Engineering and Applied Sciences.

Dr. Randy Yerrick, Fresno State University

Randy Yerrick is Dean of the Kremen School for Education and Human Development at CSU Fresno. He has also served as Professor of Science Education at SUNY Buffalo where he Associate Dean and Science Education Professor for the Graduate School of Education. Dr. Yerrick maintains an active research agenda focusing on two central questions: 1) How do scientific norms of discourse get enacted in classrooms and 2) To what extend can historical barriers to STEM learning be traversed for underrepresented students through expert teaching practices? For his efforts in examining science for the under-served, Dr. Yerrick has received numerous research and teaching awards including the Journal of Research in Science Teaching Outstanding Research Paper Award, Journal of Engineering Education "Wickenden Best Paper Award" (Honorable Mention), the Most Outstanding College Science Teacher Award from the Science Teacher Association of New York State, the Teaching Innovation Award from The State University of New York, and The STAR Award for Outstanding Mentoring. He has held fellowships in several organizations such as the National Partnership for Advanced Computational Infrastructure, the San Diego State Center for Teaching and Learning, and has on the Board of Directors for the National Association for Research in Science Teaching, served as their Director of Communications, and served for nearly 20 years as an Apple Distinguished Educator. Professor Yerrick is also a founding Member of the Science Educators for Equity, Diversity and Social Justice.

Mr. Manoj Madabhushi
Mr. Rachith Ramanathapura Ramaswamy, University at Buffalo

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Abstract

Students often struggle in the initial phases of engineering problem solving as marked by difficulties in problem setting and developing a plan for problem solving. In this study, we explored the potential for an explicated 'engineering problem typology' (EPT) to serve as an instructional scaffold for engaging students in ill-structured problem. Toward understanding the impact of EPT training we conducted pre-/post-EPT problem solving sessions. Six student pairs were analyzed and evidenced change that we argue as positive. All pairs demonstrated a shift in their problem-solving discussion from pre to post as represented by EPT discourse patterns. This includes explicit identification of the problem type, specifically referencing process stages, and in most cases, discussions aligned with EPT frameworks. The observed change in discourse patterns coincided with change in written artifacts, including more frequently used EPT terms in organizing information and a statistically significant increase in the amount of information documented in the post artifacts as compared with pre. This suggests that students were better able to consider a variety of problem relevant information after exposure to engineering problem typology. Finally, the debrief discussions revealed that students considered more problem type stages and had improved metacognition with respect to their problem-solving approach from pre to post, as reflected in their awareness and reference to various strategies and stages appropriate for the problem type. Taken together these findings suggest that EPT can provide a grounded framework to help students in developing skills and facilitate practice with ill-structured problem solving. Additionally, we believe the findings suggest that a consistent instructional reference based on EPT may provide a foundation for developing pedagogical tools to assist faculty in developing and facilitating ill-structured problem solving and overcoming curricular integration challenges.

1.0 Introduction

The origins of this research lie in engaging students in a co-curricular project program, engineering intramurals, at an R1 institution. The program brings together engineering students, from sophomore through senior year, often from multiple departments, to solve problems sourced from industry and community groups, open design communities, technical competitions, and even individual students. The program embodies many of the same features found in other co-curricular opportunities, like technical projects from student clubs and provides students with an opportunity for an experience beyond the classroom that is valued by employers.

A critical challenge encountered in the program, which impacts its scalability and limits the potential for learning, is that many students, when given an open and ill-defined problem, struggle with knowing where to begin. Toward overcoming this challenge, the program began introducing engineering problem typology [1] derived from the work of David Jonassen [2], [3]. Represented as explicated process models, problem typology serves as a basis for discussion about engineering problem solving in support of students' project planning and progress and as a scaffold for professional competency reflection [4].

Based on our own first hand experiences and the broader literature investigating the nature of engineering work [5]–[7], and studies focused on the novice to expert progression [8]–[11], we know it is critical that students have opportunities to practice and reflect on solving ill-structured problems. Such opportunities are fundamental to the development of students' ways of thinking and knowing that help them to prepare for the profession. The growth of problem and project based learning (PBL) and other active learning experiences speaks to broad acceptance that ill-structured problem solving experiences are valuable to student development [12], [13].

However, students often struggle in the initial phases of engineering problem solving as marked by difficulties in problem setting and developing a plan for problem solving. These difficulties can lead students to pursuing unproductive problem-solving trajectories that lead to frustration and reinforce behaviors of just "getting through" a problem rather than learning in ways that might translate to other contexts. As problems become increasingly ill-structured, these difficulties are exacerbated, creating a tension between instructors and students that might deter faculty from engaging in problem solving experiences that better prepare students for engineering practice. In this paper, we present an extension of preliminary findings reported previously [1]. We view the work reported here as an early step toward more substantively contributing to the development of pedagogies and instructional scaffolds that reduce such tensions and aid faculty in the facilitation of PBL experiences.

The research question investigated in this work is: *What effect, if any, does introduction of engineering problem typology have on students' initial trajectory on ill-defined problems?* To investigate this question, we explore students' initial problem solving discussions for two different engineering problem types – design and case analysis – in a pre/post study. In between the pre/post sessions, students were introduced to engineering problem typology, which was covered as part of reflection sessions as students worked on their co-curricular project.

2.0 Framework

Jonassen argued that the foremost role of an engineer is that of "problem solver" [7], [14] but the types of problems students see compared with those in professional settings are far different. The National Academy of Engineering made the same fundamental argument, noting that the origins of engineering lie in the trades with focus on producing something useful, but further points out that the formalization of engineering education has served to further disconnect engineers in practice and academic settings [15]. At the root of this disconnect is that so much of engineering education, particularly the formal curriculum conducted in lecture halls and laboratories, is focused on engineering theory and equation solving. As the predominant mode of the engineering education environment, this limits students' understanding of the reality of engineering practice – i.e. the "nontechnical, non-calculative sides" [6]; ill-structured problems, conflicting and non-technical success measures, and varied solution strategies [7], [14].

Often disconnected from context, the focus on well-structured problem solving in engineering education limits student development in important ways. For example, in practice, engineers are not just given problems to solve but also play a critical role in problem setting or framing [16]. That is, engineers in practice play a crucial role in understanding a problem in qualitative terms and then translating that understanding into quantitative terms (e.g. engineering specifications). The lack of context and opportunities to develop skills necessary for practice is a function of curricular structures that are more isolated than integrated, which fail to adequately prepare students for the profession [17].

While Sheppard et al underscored the deficits of the isolated curricular model, their calls for reform are reliant on principles that work to connect domain knowledge to real world context by more effectively leveraging existing curricular structures [17]. For example, they note the potential for integrating more open, ill-structured design and analysis problems, and leveraging laboratory courses to serve as "practice-like experiences" [17].

A variety of active learning pedagogies, like problem and project based learning, have been increasingly adopted to foster those interconnections and to address higher level learning outcomes necessary for success in the profession [12], [18]. Problem and project based learning are frequently referenced as pedagogical approaches with positive impacts on students' cognitive development, affective dispositions, and professional competences [13], [19]. For example, Galand et al. found positive impacts of a PBL curriculum on students' performance on theoretical knowledge, computational skills, and problem solving [20]. Their findings support the use of PBL in helping students to develop critical and complementary skills in engineering – i.e. acquisition of content/domain knowledge and its application in problem solving. In particular, PBL provided the most significant impact on problem solving skills [21]. Similarly, Yadav et al. reported that electrical engineering students showed greater learning gains for topics learned through PBL as compared to topics learned through lecture [22]. Considering a range of disciplines, in a meta-analysis, Dochy et al. found a generally positive view of the effects of PBL on knowledge acquisition and retention [23], a finding that was supported through a meta-synthesis by Strobel and van Barneveld [24].

Despite the growth of PBL and other active learning pedagogies, there are recognized challenges to broader adoption and implementation. In the face of these challenges, some researchers have argued for greater investigation of implementation issues, including assessment and methods to support faculty facilitation [24], [25]. These calls recognize that the shift to PBL experiences is a challenge for both faculty and students [12], [25]. This shift can be challenging for faculty because many engineering and STEM instructors have strong content knowledge but lack training on pedagogical practices rooted in active and cooperative learning [12], [13], [26]. This can lead to acute implementation challenges, like difficulty developing appropriate problems, supporting students' metacognition, and facilitating students' problem solving [27].

There are two important aspects of implementation and facilitation that the research reported here is interested in better understanding and operationalizing. First, introducing more open and ill-defined problems necessitates that some aspects of the problem, like the objectives, are open to interpretation, and other aspects, like constraints, must be set to reflect context and student abilities. This creates a relationship wherein the students and faculty cooperate to set the problem. However, student opportunities to really control problem framing, even in PBL settings, are often limited [28]. A second aspect to be considered is the facilitation of problem solving once the problem has been set. However, the development and use of instructional scaffolds that do not undermine the broader PBL goals is a specific challenge that must be considered. As one study found, if the facilitation structure is too leading, students may not engage in the learning process that that faculty seek to facilitate [29].

The research study reported here is focused on the issue of problem setting and initial planning of problem solving. We consider this a critical aspect of the initial trajectory of students' problem solving. Jonassen's design theory of problem solving [2] – specifically, problem typology –

provides a basis for instructional design of PBL experiences across the undergraduate curriculum [30]. Through research, he derived 11 types of problems [2], [3], [30], noting that for engineering the most common problem types encountered by professionals include selection, troubleshooting, and design problems [7], [14]. Our contention is that explicated problem typology frameworks – i.e. process diagrams – can be used as instructional scaffolds to support facilitation of open and ill-defined problem solving experiences. Examples of such frameworks are shown in Figure 1 for design and engineering case analysis problems. These schemas are *representative* frameworks to support discussion among students and between students and faculty as they progress in solving ill-defined problems common to engineering practice. Further, these schemas may provide a basis for metacognitive development within students as they solve problems, especially as it pertains to strategies of planning, monitoring, and controlling problem solving [31], which is vital to helping students translate learning experiences to new environments.

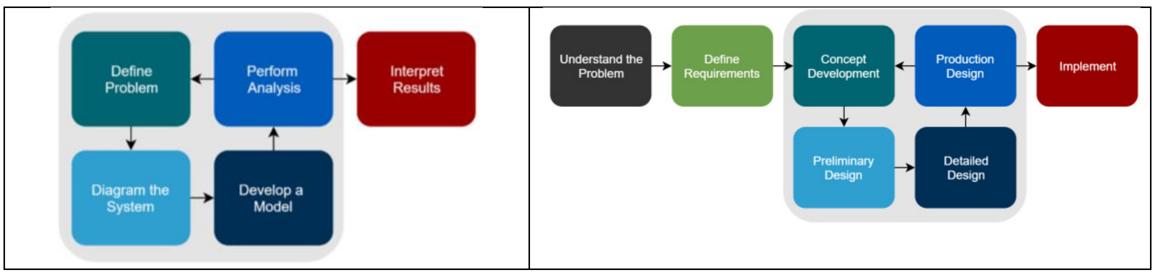

Figure 1. *Engineering problem typology diagrams for case analysis and design*

The study, described in the next section, is toward developing an understanding of the potential for problem typology as an instructional scaffold for different types of problems in engineering education. This study is motivated, in part, by Jonassen's call for research that explicitly explores different problem types [32]. The specific focus is on the initial trajectory of students' problem solving as described in the next section.

3.0 Methodology

We conducted a mixed-methods pre/post study through which we consider students' discussions of two different problems – a case analysis and a design problem. The case analysis scenario asks students to consider the feasibility of the proposed development of a water purification truck, which would be deployed to regions suffering from acute water infrastructure failures (e.g. after a natural disaster). The primary objective of the case analysis is to determine if the proposed system is a feasible alternative that could replace or reduce the need for bottled water in those circumstances. The case analysis problem description and its development was done with consideration of the problem characteristics described by Jonassen as reported in [33]. The design problem scenario asks students to consider the development of energy generating playground equipment to be designed for use in the developing world.

In between the pre/post problem solving discussions, students were introduced to problem typology (PT) as described in the next section. We began by studying how undergraduates' routines and strategies they have learned to employ in their undergraduate education shape their interpretation of ill-structured problems (pre-PT). We further explore to what degree their approaches were impacted by the introduction problem typology (post-PT).

3.1 Instructional Context and Introduction to Problem Typology

This research is conducted around a co-curricular project experience as described in the Introduction. Projects are typically a design problem or a case analysis problem. For example, one project had students involved in developing an assistive device intended to make it easier for a legally blind individual to interact with their mobile phone (a design problem). Another group worked with a structural engineer to investigate the reasons for truck-bridge collisions in the region (an analysis problem).

As part of the experience, students attended three training and reflection sessions. The sessions were a lecture style format during which students are introduced to engineering problem typology (PT). Students take part in instructor facilitated discussions that frame engineering as solving different types of problems [34], derived from the ideas put forth by Jonassen [2], [3]. The discussions consider the six engineering problem types – design, case analysis, selection, planning, troubleshooting, and diagnose-and-solve – each represented by a process diagram similar to those of Figure 1. The role of the training and reflection sessions is to get students thinking about engineering problem solving in a more abstract sense. We discuss examples of specific problem types. Additionally, the training sessions provide opportunity for getting students to think about how different problem types might interact in practice. For example, in the course of a design problem, problem types of selection (e.g. choosing materials) and analysis (e.g. in support of detailed design decisions) are likely to emerge. The training sessions are intended to help students in recognizing distinctions in the different types of problems they can expect to encounter as engineers. Finally, students take part in a reflection exercise, situating their own co-curricular project within the problem typology framework. This training time totals less than three hours.

3.1 Data Collection

Students were brought together in groups of two or three, and asked to begin to solve the real-world scenario. The groups were asked to work toward solving each problem for 10-15 minutes but were explicitly told that the problem cannot be solved in the allotted time. Instead, students were told that we are interested to understand how they discuss their approach to problem solving.

Each problem solving discussion was followed by a 30 minute debrief interview. The debrief interview was semi-structured and asked students about 1) their problem solving approach for each problem, 2) prior instruction and course experiences, and 3) their perceptions about the engineering profession and how those perceptions are evolving. At the end of the semester, as the co-curricular project concluded, we called each group back for a problem solving session (post-PT) similar to the initial session. Both the pre-PT and post-PT problem solving discussions were video recorded for subsequent analysis. In addition, students were provided a large sheet of paper and writing instruments for use during their problem solving discussions. From this data collection, we derived three distinct but related sources of data – the transcribed problem solving discussion between students, the transcribed debrief interview with researcher, and the written artifacts.

Due to the smaller sample size of participants afforded in this research – participation of students in co-curriculars is a limiting factor – we employed a quasi-experimental design. A control group would serve as a measure of no treatment nor exposure to new practices – just business as usual. Our assumption is that a pre-PT problem solving discussion assessment serves the same purpose as a post-assessment of a control group. That is, the students in the program are sophomore, junior, and senior undergraduates, who already bring to the study an established approach to ill-structured problems that has been developed over their academic careers thus far. We therefore treat the pre-PT problem solving discussion data as the control group baseline for comparison.

3.2 Qualitative Analysis of Problem Solving Discussion

Our initial methodological approach for understanding the students' pre- and post-PT problem solving discussions employed phenomenology in which we selected one pair of students and watched the recording of their discussion to consider their strategies, interpretations, and discussion of the ill-structured problem. This investigation informed an open [35] or initial [36] coding process, which was conducted collaboratively by two education researchers and two engineering education researchers. We watched the recordings multiple times, while also consulting the transcript and written artifacts. As a team we noted units of meaning from the students' discussion, like "factors," "data," and "assuming" from their pre- and post- problem solving sessions. We then transitioned to a process coding approach [36] and considered those units of meaning in the context of the problem typology diagrams (Figure 1) that had already been developed by the research team, in order to place the students' discussion in a specific stage of the process. This approach led to the formalization of a coding rubric specific to design and case analysis, which could be applied to other student pairs. The coding rubric for case analysis is shown in the Appendix.

The coding rubrics were applied to a second student pair as a way of validating the coding approach and for training graduate research assistants. The results of the first two cases are explored in detail in prior work [34]. Two research assistants applied the coding rubrics to the remaining cases, independently, using NVivo software. They compared their independent coding results and resolved disagreements until they reached an inter-rater reliability of at least 0.70 (Cohen's Kappa coefficient in NVivo [37]). Resolution of discrepancies and final results were reviewed with a lead researcher as a final step of the process.

3.3 Quantitative Analysis of Written Artifacts

Part of our analysis considers the written artifacts generated by the students during the pre/post problem solving discussions. An example of pre and post artifacts from one of the student groups for the design problem is shown in Figure 2.

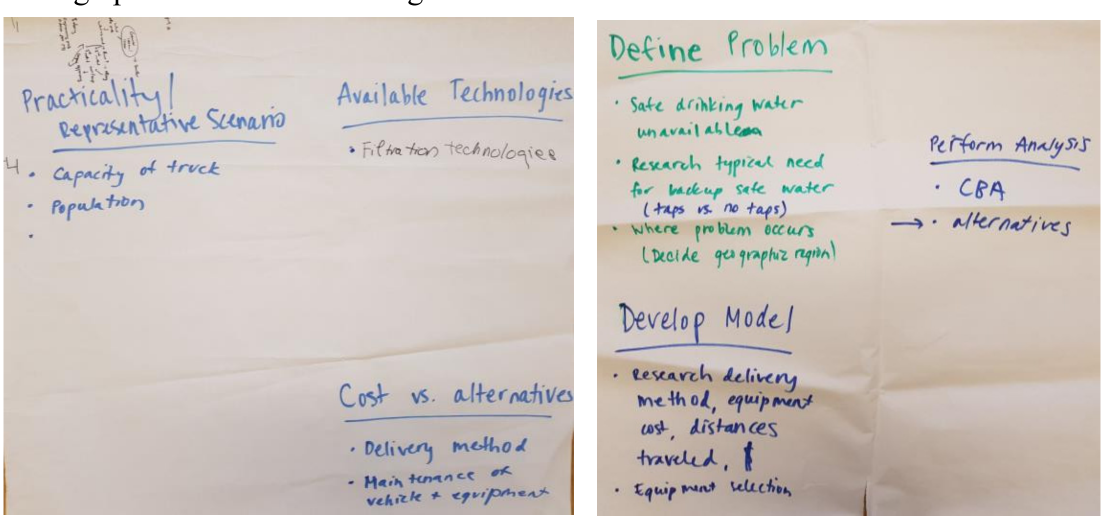

Figure 2. *Examples of written artifacts from pre (left) and post (right) case analysis problem discussion from one student pair -- Keith and Cora*

A general trend we observed among students from pre to post problem solving discussion is an increase in the information that they wrote down and changes in the organization of information. Toward quantifying how these artifacts changed from pre to post we developed a simple data reduction approach by answering the following questions for each artifact:

- How is information organized in the artifact?
    - UL = unstructured list of information with no categories or obvious structure or relationship
    - SSL = semi-structured list of information with clear break up of different info but no headings/categories
    - SL = structured list of information with clear headings to categorize the information in some way
    - CM = concept map; connected nodes of concepts or ideas
- How many problem typology terms are used in the artifact?
- Is any information categorized/organized by problem typology stages?
- What types of information appear (qualitative, quantitative, diagrams)?
- How many bits of information are contained in the artifact?

To calculate the bits of information, we transcribed the qualitative and quantitative information into a text file (.txt) and found the file size in bytes using Matlab, which was converted to bits. In transcribing the artifacts to a text file, the following rules were applied: 1) for quantitative information, include the number and unit, and 2) ignore bullet points.

3.4 Qualitative Analysis of Debrief Discussion

For the research question investigated in this work, the most relevant aspect of the debrief discussion relates to student metacognition as captured in responses to questions about their problem solving approach, strategies, reasoning, etc. Through a semi-structured interview, the student pairs were asked questions like: "Tell me what you wrote/drew and why?"; "What did you do to solve this problem?"; "What strategies did you use to solve this problem?"; "What else do you need to solve this problem?"; and "What would be the next couple of steps to solve this problem?"

Toward understanding if and how students' responses to those questions changed from pre to post sessions, we coded transcript responses associated with each of the interview questions above using NVivo software. We then performed a word frequency analysis for this subset of questions and looked for differences in keywords and terms that would be associated with the different problem types. For example, in discussions about strategies for solving an analysis problem, we anticipate that students would use the term analysis or synonyms (e.g. calculate, calculations). The keywords and terms were derived from the coding rubrics, which capture key concepts about problem typology that students were introduced to in the training sessions. We explored differences in student responses from pre to post.

4.0 Results

A total of 10 student groups (25 students) took part in the pre-PT problem solving discussions but only six cases are analyzed here. These were the only six cases in which the students completed both the pre and post problem solving discussions. The six student groups are: Ron and Jeff, Sam and Madison, Mike and David, Rich and Jenny, and Keith and Cora. We note that two student pairs – Rich and Jenny and Keith and Cora – each had a third member in their pre sessions that did not return for the post. We also note that the post session for Cody and Amelia was conducted virtually since their data was collected during COVID-19 lockdown that resulted in remote-only engagement between students and researchers.

We report results of the artifact analysis for both the case analysis and design problem in Section 4.2. However, for the problem solving discussion analysis (Section 4.1) and debrief interview analysis (Section 4.3) we limit our results to the case analysis problem in order to keep the manuscript to an acceptable length. Additionally, we know that analysis of students activities and behaviors in the novice/expert paradigm is well represented in the literature for design (e.g. [9]–[11], [38]) but case analysis seems a less studied explicit problem type.

4.1 Results of Problem Solving Discussion Analysis

Results from analyzing the problem solving discussion for the case analysis problem are shown for three student pairs in Figure 3. These diagrams show a side-by-side pre-/post-PT comparison and are representative of the discussions for all six student pairs. The graphs depict the ways in which students' discussion transitions among process stages in their initial thinking about solving the problem. Each phase is represented by a color-coded circle whose radius is equal to the number of exchanges between students in that phase.

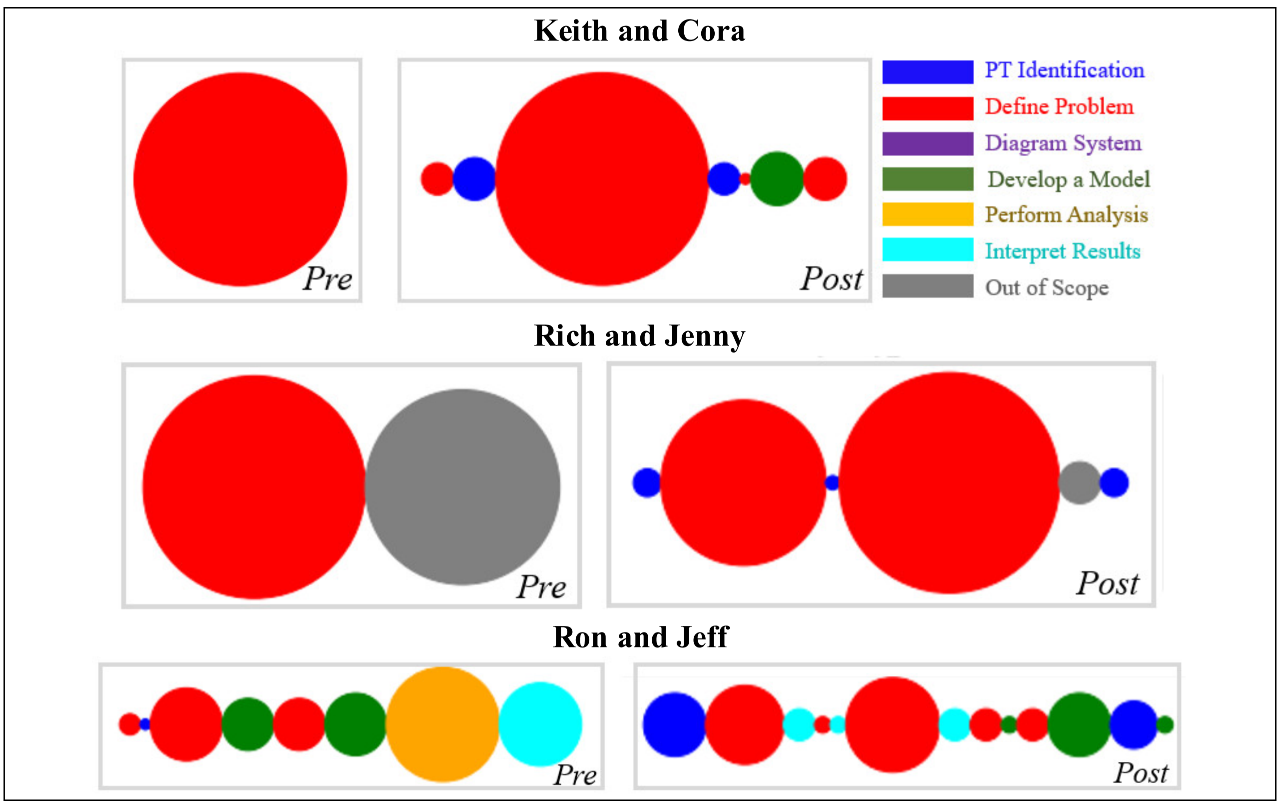

Figure 3. *Case Analysis Problem Solving Discussion Patterns for Three Student Pairs*

From Figure 3 we note that all the student pairs' discussion patterns changed, which is also true of the three pairs not pictured. We observed two changes in the problem solving discussion patterns of the student pairs. First, is explicit reference to the type of problem being considered. In the pre session, only one of the five groups explicitly referenced the problem as a specific type during the discussion (Ron: "So basically what we're trying to do here is...perform an analysis and see whether this is like effective or not, right? [We're] tasked to develop an initial analysis to inform these agencies."). However, in the post discussions, all six groups made explicit reference to the type of problem as part of the problem solving discussion. For example, in the post case analysis of Mike and David (not pictured), they first identify the problem type and define the scope of the problem based on their understanding of the problem type.

> Mike: "Alright. Right away. It's a case analysis problem."
>
> David: "Yeah"
>
> Mike: "We're not going to be designing anything. We're just analyzing it"
>
> David: "And decide which ones serve our purpose?"
>
> Mike: "Well, we don't make the decision. We're just basically just looking at each and providing the information."

In this exchange, Mike and David came to an explicit agreement about their interpretation of the goal of their problem solving, invoking differences among problem types as it relates to the problem goal. This type of exchange among student pairs in the post differs from the pre where there were no explicit agreements about the problem goal.

A second change we observed is that two out of three groups reduced or eliminated their out of scope discussion from pre to post problem solving discussions. We coded elements of students' problem solving discussion as "out of scope" when their discussion was not germane to the fundamental problem (i.e. they seemed to be solving a different problem). For example, in the pre case analysis discussion Rich, Jenny and Karen, briefly discussed a need to fix the failed infrastructure to solve the water purification problem.

> Karen: "I feel like... the problem stems from infrastructure failure. So, what are they going to do about that? Trucks can't just...fix that."
>
> Jenny: "So that would be like alternate option."
>
> Rich: "Yeah"

From pre to post we note that Rich and Jenny reduced their out of scope discussion. In the pre, the out of scope issues dominated the second half of their discussion, such that they never recovered before the discussion was truncated. However, in the post, while some discussion was out of scope, they recovered from being out of scope before their discussion was ended by the researcher. For example, in the post case analysis discussion of Rich and Jenny, Jenny talks about implementing a specific water purification technique in the flatbed truck that uses a certain algae but is experimental and not listed among the options in the problem statement. Rich is quick to point out that this is out of scope of the problem as their task is to perform analysis. He adds that the specifics of the purification system are more of a design problem to which Jenny agrees.

> Jenny: "I know actually I know one solution like they use that algae, they derive something from algae and then they create a water ball and then we can eat in wholly into all like the algae. But I forgot the name of that."

Rich: "So is that like a container?"

Jenny: "Yeah, a container, like you can eat up the whole container. So we can say that... like the delivery truck can have these inside."

Rich: "So I think, uh, like out of the scope because we were trying to do a feasibility analysis of this concept right here. So, like that's maybe a design problem maybe."

Jenny: "Yeah."

Like the initial agreement of problem type between Mike and David, we find that knowledge of problem typology allows Rich and Jenny to redirect their discussion when it appears start down a less productive problem solving path.

4.2 Results of Written Artifact Analysis

The results from artifact analysis for the case analysis problem are shown in Table 1. Whereas most student pairs collaborated on the development of the written artifact, Ron and Jeff each created their own written artifacts and thus, are analyzed separately.

Table 1. *Artifact analysis results for case analysis problem (grey rows = post)*

		Ron	Jeff	Cody + Amelia	Keith + Cora	Madison + Sam	Mike + David	Rich + Jenny
Organization of Info	Style	UL	UL	SSL	SL	SL	UL	SL
		UL	CM	SL	SL	SL	SL	SL
	PT Terms	0	0	0	0	0	0	0
		1	1	2	3	3	1	3
	PT Stage Category	0	0	0	0	0	0	0
		0	0	1	3	0	0	1
Diagrams		0	0	1	0	0	0	1
		0	0	0	0	0	0	0
Bits of Info	Overall	1576	984	2992	1536	2640	1240	2528
		3024	2944	7480	2376	2288	4632	4008
	Quant	96	888	0	0	88	144	0
		0	0	0	0	0	0	0
	Qual	1480	96	2992	1536	2552	1096	2528
		3024	2944	7480	2376	2288	4632	4008

There are three notable differences in the artifacts from pre to post. First, there is evidence that students adopted and used more of the problem typology terminology within their written artifacts, with all groups having at least one instance in the post for both case analysis and design as compared to none in the pre artifacts. Second, the results show that while some students documented quantitative information in their pre artifacts, especially for the case analysis problem, none included quantitative information in their post artifact. Third, there was an increase in the overall bits of information in the artifacts from pre to post for both the case analysis and design problem, with the exception of the post case analysis from Sam and Madison. The average bits of information increased from pre to post by 1893 bits for case analysis and by 1364 bits for design.

We conducted a Kruskall-Wallis test to compare the pre/post medians for overall bits of information using Matlab [39], [40]. We found that the differences were statistically significant at a significance level of 0.05 for both case analysis (p = 0.0253) and design (p = 0.035).

4.3 Results of Students Described Strategies Analysis

The results from the pre/post word frequency comparison for the case analysis problem debrief is shown in Table 3, including the frequency of the term (Count), the number of student pairs who used it (Groups), and which pair used it (represented by first initials of each student in the pair). We limit our results to terms where we found differences in frequency. Further, we have categorized the terms to reflect the meaning and activities as described by the students.

From the results of Table 3, we see that in the post, students made more frequent reference to the idea of performing analysis, developing a conceptual model (i.e. diagram the system), defining the problem, and developing a model as compared to the pre. We also note that more of the pairs used these terms and ideas as part of describing their problem solving approach in the post as compared to the pre. Sam and Madison (SM) stand out as a student pair that did not invoke any of these terms or ideas in the post problem solving debrief discussion.

Table 3. *Word frequencies for student described strategies to problem solving from pre and post for case analysis*

	Pre									Post								
	Term	***Count***	***Groups***	***RnJf***	***KC***	***SM***	***CA***	***MD***	***RhJn***	***Term***	***Count***	***Groups***	***RnJf***	***KC***	***SM***	***CA***	***MD***	***RhJn***
Perform Analysis	analysis	1	1	x						analysis	20	5	x	x		x	x	x
	calculate	1	1						x	analytical	3	1				x		
	calculations	1	1	x						analyze	2	2					x	x
	math	1	1			x				analyzing	2	2	x	x				
Gather Info	data	19	4		x		x	x	x	data	9	3		x		x	x	
	information	12	5	x	x	x	x	x		information	3	2		x				x
	research	16	5	x	x	x	x		x	research	8	3		x		x	x	
Conceptual Model	diagram	1	1				x			diagram	3	2	x					x
	drew	1	1				x			diagramming	4	3	x	x		x		
	conceptual	1	1						x	diagrams	1	1				x		
										draw	1	1	x					
										drawing	1	1	x					
										conceptual	3	2				x		x
										conceptually	1					x		
Define the Problem	define	2	1						x	define	3	2		x				x
	defining	1	1						x	defined	3	2		x				x
										defining	8	4	x	x		x		x
Develop a Model	model	0	0							model	10	4	x	x		x		x
	test	4	3	x		x	x											

The discussion related to gathering information in the pre reflects a recognized need for data or information relevant to the problem (e.g. "…And then data about effective filtering systems and like what's effective. What's most effective for what, where? Like what problems could it solve? How much it would cost.") and a more general need to conduct research to better understand the representative problem scenarios (e.g. "So research each area, defining what they need."). At times in the pre, references to research lacked specificity and just reflected a need to inform their understanding (e.g. "Well then as you asked I would say to solve this problem, we definitely need to acquire more data by research like Google, Wikipedia articles, that stuff that could be the next data.")

From pre to post debrief discussion, the student descriptions shift from a focus on gathering information to considering other strategies or steps associated with analysis problems. Most notable is increased reference to performing analysis as part of their problem solving. In the pre, there were few references to analysis actions (e.g. “Now I'm going to look at all the different ways that we can use this, this information to create a better outcome in these cities. And then after that, um, math for sure, just the math or like total cost, um, implementation and all.”). Only one student, Rich, refers to performing analysis, using “calculate” – as a step in a larger process of solving analysis problems that he learned in class: “Um, because it pretty much narrows your focus on like the problem is sort of like, cause like you're just given like a general like problem but then you're supposed to narrow that down and figure out variables that you have to consider and how you're going to calculate that.”

In the post, there are more references from students to performing analysis as a specific step in solving an analysis problem. For example:

> Amelia: “And we kind of just threw out some different things that we need to know or need to look into to actually perform the analysis.”
>
> Keith: “Um, and then from that step we would then go to performing analysis of whether it be worth to, to pursue this alternative method or if we should just buy a case of water, you know, and then, but that depends on how big the problem is where occurs and stuff like that.”
>
> Rich: “So like the first like define the problem, then you like diagram the system, create conceptual model, and then you go to developing a model and then you perform analysis on the model, interpret results. And if that, those results aren't good that you restart that whole cycle.”

We note similar results for students’ thinking about conceptual representations as having a role in the problem solving process as reflected in discussion about diagrams, drawings and references to concepts. In the pre, only one pair – Cody and Amelia – draw a picture and reference it as a conceptual model. Again, Rich references classroom learning: “I wrote down, I mean we were taught in my class, like, to get to define the problem first before actually like making of the conceptual model.” However, in the post, two additional groups reference diagramming or development of a conceptual representation as playing a role in their thinking.

> Jeff: “I mean I would say that this kind of method of drawing now, like this is diagramming the system.”
>
> Ron: “I think defining the problem is the big, big one. Diagram the system and model is more what probably would be our next steps. Like things that we would consider if we had more time.”
>
> Cora: “I kind of lump together diagramming the system and developing a model.” (Note: Cora and Keith did not actually draw a diagram.)

Finally, we note a change in the idea of developing a model from pre to post debrief discussion about problem solving strategies. In the pre, no students used the term “model” as something to be developed to support feasibility analysis. Instead, students referred to the idea of testing by building the system as their way to model performance (e.g. “Build a system, test it, you know?”).

In the post, students referenced the development of an (analytical) model as a way to understand the performance and tradeoff, and placed building a system as a form of model validation.

> Keith: "So we moved on to, um, how we would want to develop a model for this, uh, analysis, uh, which included like the research, uh, like the delivery methods and, um, equipment in everything was around cost.
>
> Jeff: "So I just listed, um, a lot of different things like parameters almost, especially for the decision matrix part of it when you're considering which purification where I would be best suited to send to a place of like costs, like how, how efficient it is, um, uh, how it would be transported, time it takes to set up and send these out. Just a lot of different factors that you would, if you were to set up a model that could compare like all."
>
> Amelia: "I mean, it would be great to have like research and someone else's data to do it. But if we really wanted to prove our analytical model then, we'd want our own kind of data, I assume."

5.0 Discussion and Implications

The findings from this study provide insights related to the fundamental question about the impact of introducing problem typology on students' initial problem solving trajectory. This research is motivated to help students, who often struggle in the initial phases of ill-structured problem solving. We further situate this study in the context of helping faculty in facilitating student practice with such problems, which they might introduce in the classroom. In the results, we noted three differences from pre to post problem solving sessions among students and the observed changes suggest ways in which problem typology might be used as an instructional scaffold in ill-defined problem solving environments.

First, we saw that in the post, all students referenced problem typology to establish an initial agreement on the goal and scope of the problem scenario. Further, some groups evidenced use of problem typology as a metacognitive aid to direct and redirect their discussion about the problem (e.g. to limit "out of scope" discussion). This differs from the pre sessions, where only one student explicitly mentioned the problem type in the pre (but did not get a confirmation from his partner). Similarly, in the pre none of the student groups were reflective about the relevance of their ideas and strategies during the discussion with their peers, which may explain some of the out of scope discussion. This finding suggests that problem typology can facilitate interaction among students in directing their inquiry and supporting discussion along productive problem solving pathways. It also suggests that problem typology can help faculty to overcome challenges of facilitating PBL experiences [27]. Specifically, it may provide a common framework by which students and faculty can negotiation problem framing/setting and discussions of appropriate steps and strategies for problem solving without getting too specific about exactly how to do it, which can undermine higher level learning outcomes of PBL [29].

We also saw that students developed more information rich written artifacts in the post compared with the pre discussions. This is an important issue because ill-structured problems require a greater coordination of information seeking and communication within the team. However, students have limited experience with information rich problem contexts. As described by Buccarelli, the well-structured problems that students typically encounter "teaches them not to see" and focuses their problem solving practice on reducing problems to math exercises [41] and plug-and-chug approaches [7]. Even in well-structured problems, novice problem solvers might struggle to find the salient information [42]. Thus, when students encounter ill-structured, information rich problem scenarios their lack of practice with such problems makes parsing of available information and consideration of other possibly relevant information more difficult. The artifact analysis suggests that problem typology might help students in considering and organizing available information, questions that need to be answered through additional information gathering, and planning of activities they might take in solving the problem.

Finally, through the word frequency analysis of the reflective interview, we found that in the post session, students described elements of problem solving that covered more stages of the underlying problem solving process. This stands in contrast to the pre session where we found that students focused much of their reflective talk on research and information gathering activities but did not evidence that they knew how to relate those activities back to other relevant problem solving activities. This was especially true of "develop a model" to support analysis; there was scant evidence that the students were explicitly thinking about developing an analytical model as the core activity of their problem solving in the pre session. Instead, students were more likely to reference physical testing, despite the fact that much of their engineering problem solving experiences are rooted in analytical modeling; a tendency among engineering students that has been reported elsewhere [43]. The pre to post change observed in this study suggests that problem typology, in representing multiple stages and associated activities, can help students to recognize more of and connect the various problem solving activities relevant to a specific problem type.

Overall, students demonstrated a more coordinated problem solving discussion in the post session. This suggests that problem typology provided a shared metacognitive framework for monitoring and regulating their discussion and reflection afterward [31]. The observed changes from pre to post within the three data sources explored in this study supports our contention that problem typology can provide an instructional scaffold to facilitate ill-structured problem solving experiences. We see two implications for concurrent implementation and further research. First, it might provide a consistent instructional reference across the curriculum that may help to overcome curricular integration issues [17]. Consider three possibilities:

1) To initiate students into thinking about different types of problems, we envision implementation of different types of problems, at varying levels of difficulty, for first year courses. This would allow for comparing the problems across types and difficulty levels.

2) Integrating problem typology based reflection across the curriculum as a way to help students regularly situate their learning and experiences in a more abstracted framework would help to foreground problem solving strategies that translate to new problem solving environments.

3) Modifying common existing courses – e.g. engineering lab courses – around problem types. For example, experiments represent an analysis approach used by engineers to understand and model phenomena. A natural sub-problem is to design an experiment

(experiment and apparatus) and a likely sub-problem would be troubleshooting the experiment. Within an existing course experience, we find opportunities to relate learning about technical concepts into problem solving frameworks representative of the profession.

A second, and related implication, is that consistent use of problem typology may provide a basis for helping students in their transition to more independent, less structured problem solving environments, like co-curriculars, internships/co-ops, and even entry-level engineering positions. If problem typology is leveraged consistently, there is opportunity to study the impact of consistent framing of engineering in helping students to acclimate to these other problem solving environments.

We note three limitations of this study. First, this study is comprised of a small sample size. Second, we note that the study involves student participants whose voluntary participation in both the research and the co-curricular experience may suggest that they are more invested and engaged and therefore more likely to exhibit measurable changes in behavior from pre to post. This limits any notions of generalizable outcomes in the broader student population. A third limitation is the pre/post experiment design where the pre represents a control group for baseline comparisons and use of the same problem statement. These limitations are all elements to be mitigated in future research studies.

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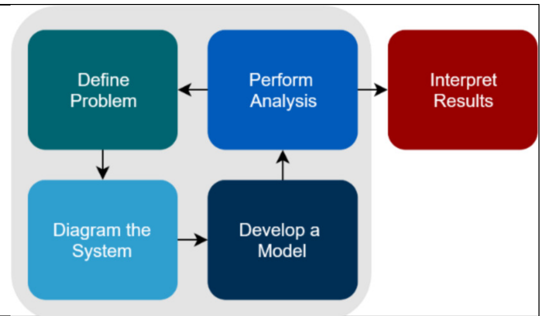
Appendix 3 Engineering Case Analysis Coding Rubric

The role of a formal engineering analysis is to support decisions (e.g. decisions necessary in the design of an artifact) or recommendations to others as in a trade study.



Process Stage	Student action/thinking as revealed through talk	Code
Problem Typology	Discussing the type of problem to be solved	PT:ID
Define Problem	Discussing the objective of the problem	DP:OA
	Discussing or identify known parameters	DP:KP
	Discussing or identify unknown parameters	DP:UP
	Discussing the level of detail or precision	DP:LD
	Writing lists or developing concept maps as a form of problem representation	DP:PR
Diagram the System	Discussion and drawing of a diagram that conceptualizes the system or subsystem in terms of behavior and function	DS:Dia
	Annotation of diagram and/or accompanying description to document behavior and parameter interactions/relations	DS:Ann
Develop Model	Discussion of modeling method – physics/equation-based model from known theory and/or empirical model	DM:MM
	Discussion of assumptions necessary for model development	DM:Assum
	Discussion of data and information acquisition	DM:DAQ
Perform Analysis	Discussion of an analysis tool/environment (e.g. simulation software, Excel)	PA:Tool
	Discussion of model execution challenges	PA:Execute
	Discussion of validity of model results	PA:Valid
Interpret Results	Discussion of presenting or interpreting results – i.e. how they might be presented or what is required for interpretation in the context of the objective	IR:Obj
	Discussion of results in terms of how they might be sensitive to certain parameters or assumptions and the uncertainty associated with those elements	IR:SA
	Discussion of analysis or model limitations that result from assumptions, current states of knowledge, technical capability, etc.	IR:Lim
	Discussion of conclusions/recommendations based on the results of the analysis process	IR:Rec