Understanding the Effect of Scaffolding on Introductory Ill-Defined Problems in Engineering Education

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***Abstract*—This full research paper examines the effect of scaffolding on students' engagement with engineering judgment while solving an open-ended modeling problem (OEMP) during an introductory statics course. While traditional engineering coursework involves well-structured homework problems, research shows that open-ended design problems offer opportunities for students to develop fluency in problem solving and practice the use of engineering judgment. However, the transition from traditional, well-structured problems to OEMPs can be difficult for students, highlighting the critical role of scaffolding in introductory OEMP design [1].**

In this paper, we interviewed the professor who created and assigned the OEMP to understand the goals of the scaffolding. Next, we analyzed the OEMP written assignment for scaffolding that elicits the use of engineering judgment and statics concepts. Using both data sources, the professor's goals and assignment analysis, we coded a video transcript of collaborative work sessions from a group of students as they worked through the OEMP for engineering judgment and identified if students used the correct static concepts in their discussion. The implications of the paper revolve around identifying the level and type of scaffolding that initiates engagement in engineering judgment and statics course material, as well as strategies for improving scaffolding of open-ended problems. These insights aim to assist educators by highlighting effective scaffolding techniques that better align professor's goals with the student takeaways.

Keywords—Engineering Judgment, knowledge transfer, problem solving, engineering curriculum

I. Introduction

Professional engineers solve complex, open-ended, and ill-defined problems that have conflicting goals, multiple solution methods, and non-engineering success standards [2]. These workplace problems differ significantly from the typical coursework completed by engineering students, which tend to be well structured with single solution paths [2], [3], [4]. However, these types of structured textbook problems are insufficient in preparing students to tackle complex work-place problems. In fact, most engineering students do not encounter ill-structured design problems until a senior design course. The goal of our work is to better prepare students for their professional careers by introducing students to ill-defined problems early on in their engineering education.

Open-ended modeling problems (OEMPs) serve to introduce students to the structure and concepts found in work-place problems, featuring multiple solutions, the use of engineering judgment, and the idea of non-engineering constraints and success standards [2], [5], [6]. This allows undergraduate engineering students to begin to develop an engineering mindset well before graduation. When instituting these problems, professors have a variety of goals in mind while aiming to satisfy the Accreditation Board for Engineering and Technology (ABET) standards [7]. OEMPs solved in a group setting provide the ability to satisfy several ABET accreditations at once, and the corresponding ABET outcomes. The outcomes more relevant are Outcome 1, an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, Outcome 2, ability to apply engineering design to produce solutions that meet specified needs and Outcome 5 an ability to function effectively on a team.

Previous research on OEMPs has found that students feel overwhelmed, frustrated, and confused when encountering their first ill-defined engineering problem [8], [9]. Therefore, it is crucial to examine the scaffolding of these introductory OEMPs. This research paper aims to better understand how to support students through their initial encounters with ill-defined problems, while still ensuring that the problem retains enough open-ended structure to promote students' conceptual learning and elicit engineering judgment. We explored the scaffolding of a semester-long OEMP given to freshmen and sophomore students during their first statics course to answer the following research questions:

1. What aspects of the OEMP scaffolding are productive or prohibitive towards students engaging in engineering judgment?
2. What aspects of the OEMP scaffolding are productive or prohibitive towards students engaging with course material?
3. Are the professor's goals for students achieved with the chosen scaffolding?

II. Background

Scaffolding refers to a pedagogical process in which a teacher or more knowledgeable peer assists a learner by designing the learning task and providing guidance througmhout so the learner can solve problems that would be otherwise out of reach [10]. This assistance is tailored to a learner's specific needs and abilities, aiming to help them accomplish tasks while also fostering a rich and meaningful learning experience [11]. Gradually, as the learner gains confidence and competence, the scaffolding is adjusted such that the provided support is lessened to encourage greater independence and agency towards problem-solving. The concept of scaffolding is firmly rooted in Vygotsky's Zone of Proximal Development theory, stating that scaffolding acts as a crucial bridge between a learner's current capabilities and their ability to solve an out-of-reach problem [12]. Scaffolding facilitates the development of problem-solving skills, critical thinking, and independence in learners by providing the necessary support and guidance to navigate challenging tasks effectively.

Research in the learning sciences has focused on creating disciplinary authentic tasks and then worked to understand how scaffolding can make a task more attainable for the student and more productive for learning [13]. While the concept of scaffolding is well established, its application to examining assigned engineering tasks is limited, especially ill-defined problems. One study examining a bioengineering lab investigates how improved scaffolding affected performance [13]. Our work follows this trend in creating and assigning a task closer to the work of a professional engineer and, now, examining how to better construct the assignment. We explore the effect of scaffolding on introductory OEMP design as the scaffolding of a problem is a crucial factor in whether a task actually facilitates student learning. Additionally, we seek to understand the effectiveness of different scaffolding in allowing students to practice using engineering judgment.

In the context of this study, our definition of scaffolding refers only to planned scaffolds and does not include interactional scaffolds. Planned scaffolds refer to the specific, written guidance integrated into the problem statement, while interactional scaffolds refer to any additional assistance provided by the instructors, either in lecture to all students or in a small group environment during the professor's office hours [15]. Both types of scaffolds represent the full spectrum of guidance provided to students when tackling the pool lift OEMP because students are provided written problem statements, but may also seek help after class in office hours or through scheduled appointments with the professor. However, we do not have specific data on the interactions between professor and students during lecture or office hours, and therefore do not consider interactional scaffolds in our analysis.

III. Methodology

A. Positionality

This paper aims to analyze the scaffolding of an OEMP given in a second-year statics course to students at an R1 university. The first two authors are undergraduate engineering students who completed the pool lift OEMP during their sophomore statics course. Both students received an A in the class and had a positive experience while solving the OEMP. The third author is the principal investigator of a larger engineering education research project to implement and study multiple OEMPs and engineering judgment. The fourth author is the professor who designed the pool lift OEMP studied in this paper and has implemented the project in her introductory statics course every semester since Fall 2020.

B. Study Context

For the pool lift OEMP studied in this paper, students are tasked to work in randomly assigned teams of 4 to 5 students to design a portable pool lift model. Over the course of the semester, the project is broken down into five parts and a final report. The project is designed to sequentially follow the course material so students can directly apply what they are learning in class to the part of the OEMP they are working on. For each part, students are first asked to complete an individual assignment where they answer conceptual questions to guide their understanding of the OEMP. Then, in their groups, students work together to design the portion of the pool lift prompted by the corresponding section of the project. At the end of each part students are asked to state all assumptions made during their analysis and to provide a justification where necessary. Some parts of the OEMP encourage students to apply conceptual knowledge learned in class to solve for dimensions or elements of the design, while other parts guide students to use their judgment or outside sources to choose a reasonable answer. Therefore, different tasks prompt students to either use statics concepts or engineering judgment while solving the OEMP. The following table outlines each of the 5 parts and the associated student deliverables:

Table 1: OEMP Parts and Associated Student Deliverables

OEMP Part	Student Deliverables
Part 1	Select dimensions for the lift arm assembly that ensures the chair is capable of a desired vertical range of motion without overextending the hydraulic and record the user weight limit.
Part 2	Assign the base and stabilizing arm dimensions and determine the base counterweight amount to prevent tipping.
Part 3	Compute the reactions at each joint seen in Figure 1 (B, C, D, E, G, and H) at a range of alpha angles to determine the maximum load.
Part 4	Analyze the internal forces and moments within the vertical member ABC to draw shear force and bending moment diagrams for the member.
Part 5	Use the external and internal force and moment analysis to determine the diameter of the hydraulic cylinder GH and select the size and materials for the vertical member ABC and pins G and H.
Final Report	Write a report that demonstrates their model assumptions, calculations performed, design justification, and conclusions on the competency of the completed model.

Students are provided with Figure 1 as a reference image while they work through the OEMP:

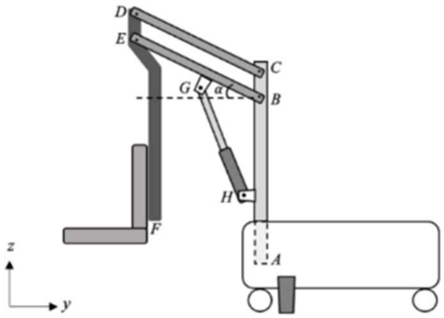

Figure 1: Pool Lift Diagram Provided to Students in Part 1 of the Assignment.

C. Data Sources

Previous OEMP studies have focused on students' problem solving process [6],[16],[17] or how instructors have created OEMPs [5]. This paper is our examination of the intersection between the two through scaffolding. We gathered multiple data sources, both from previous studies and for the purpose of this study, to look at the interaction between the professor's intentions and what the students actually do.

Data Source #1: Interview with Professor Nightingale

The first source of data for this paper is an interview with the fourth author who is the professor who designed the OEMP and assigned the project in her statics course. The interview was collected as part of this scaffolding study and its purpose was to understand the level of scaffolding in the OEMP and the professor's goals while designing and assigning the OEMP in her classroom. The questions were created by the undergraduate co-authors that have completed the project. Each co-author created a set of questions for the interview and the third author reviewed and refined the questions. The interview was conducted by the student co-authors and using an AI generated transcription of the interview, the co-authors compiled a list of the professor's incorporated goals.

Data Source #2: Written OEMP Assignment

The second source of data is the written OEMP assignment, comprising five smaller parts and authored by Professor Nightingale. We first analyzed each part and identified which statics concepts were scaffolded into the specific tasks. We did this by identifying key phrases in the document that address specific statics concepts. For example, in the assignment students are asked to "Perform a Static Equilibrium analysis for [their] team's agreed upon worst-case positions. FBDs and equations should be created and analyzed in 2D." The term "static equilibrium analysis" is a clear indication that students must use moments, FBDs, and equilibrium equations to accomplish that task.

We additionally outlined where students were expected to exercise engineering judgment to serve as a guide for establishing whether the written OEMP scaffolding was effective in guiding students to engage in the productive beginnings of engineering judgment. An example of how we interpreted the written assignment for engineering judgment can be seen in the following statement pulled from the document, "As a team, discuss reasonable ranges for the Pool Lift dimensions with functionality in mind." Our interpretation of the underlined words is to guide students to apply real world knowledge and outside research to the engineering problem. The statement asks students to consider reasonableness and functionality which goes beyond equations and numbers, and guides students to use rationale for their design choices. To verify that the scaffolding coincides with engineering judgment expectations and the correct statics concept, the fourth author reviewed the analysis.

Data Source #3: Student Group Transcript

The third source of data is video recorded sessions of a group working through each part of the OEMP over the semester. The sessions were recorded during the Covid-19 pandemic Spring of 2021, when the group meetings were held on Zoom. These videos were originally recorded as part of a broader OEMP study examining students' use of engineering judgment, with the initial analysis available here [18]. In this paper, we utilize the previously collected data and apply a new analysis to explore how students interact with the problem scaffolding. The videos were transcribed by another member of the research team and compiled on an Excel sheet. During analysis, we first used the statics concepts pulled from the assignment document analysis (data source 2) to determine if the students were incorporating the correct concepts into their discussions and design process for each OEMP part. We analyzed the group transcripts with a pre-established taxonomy (from a forthcoming paper [17]) that identifies the productive beginnings of engineering judgment. Then we reduced the taxonomy to the version below to only include the type of engineering judgment engagement that we saw from students [6], [16], [17].

Engineering Judgment Taxonomy:

E1: Making an assumption with no justification
E2: Assumption considers the user, client, or manufacturer
E3: Assumption makes the model more realistic, accurate, representative, or typical based on the student's research or experimentation for the class
E4: Assumption makes the model more realistic, accurate, representative, or typical based on the student's personal lived experience outside the classroom
E5: Assumption makes the model solvable
E6: Assumption models what the student thinks is the worst-case scenario
E7: Assessing the reasonableness of assumptions that the student made
E8: Assessing the reasonableness of the output of the model
E9: Using a technology tool to help with analysis/computation
E10: Overriding a calculated answer considering the user, client, manufacturer, or safety

An example of how we coded the transcript for both statics concepts and engineering judgment is shown in the following utterance made by a student in the recorded videos:

> Pool lifts have to be able to maintain a static load of 1 and a half times that [weight]. *So when we're doing the moment* we have to consider…it based off of 450 pounds instead of 300.

The part of the quotation in italics shows that the student is using the statics concept of moment calculations in their analysis of the pool lift counterweight. The underlined portion shows a student using a worst-case scenario in order to make the model safer or more accurate, therefore, we identified this as making a judgment, specifically, “Assumption models what the student thinks is the worst-case scenario (E6).”

D. Limitations

The pre-existing group transcripts from 2021 (data source #3) are part of a larger ongoing research project to examine the effects of OEMPs on engineering judgment. The data was not initially collected for this scaffolding analysis study. Additionally, the sample group is small and mainly comprised of high-achieving students. For example, evidence in the transcript shows that this group used various technologies without being explicitly asked to, such as MATLAB to solve for dimensions at various alpha angles, and AutoCAD to draw FBDs. Due to this, we are limited in our ability to analyze correlations between scaffolding and groups that did not perform highly on the project. Additionally, the group transcript was collected in Spring 2021, therefore we are only able to analyze the first iteration of this OEMP, despite the problem having undergone several scaffolding improvements in the past four years based on student feedback.

IV. Results and Discussion

A. Professor Interview Results

Upon deciding to design an OEMP for her introductory statics course, Professor Nightingale consulted with the third author, who specialized in ill-defined engineering problems, and was provided an initial list of the elements to create an OEMP:

1. Open-ended, meaning there is no single correct answer [3]
2. Set in a real-world context or involve a real-world object [19]
3. Students apply theories of behavior taught in engineering science courses [20]
4. Students practice engineering judgment [21]
5. The use of mathematical models in design and analysis

During our interview, Professor Nightingale’s communicated goals incorporated the elements from this list in conjunction with her own personal goals for the project. Based on the communicated goals, we identified three impact areas to which each professor goal pertained:

1. Improve students conceptual understanding of course material
2. Prepare students for real world engineering
3. Improve course structure and teaching methods

The professor's goals were then sorted by impact area, and Table 2 provides a goal ID for ease of reference and shows which goals correspond to each of the three impact areas.

Table 2: Professor Goals

Impact Area	**Professor Goal**	**Goal ID**
Improve students conceptual understanding of course material	Reinforce what students are learning in class	G1
Prepare students for real world engineering	Expose students to real world problems (a problem that has multiple solution paths and does not explicitly give only information needed to solve problem)	G2
	Introduce students to engineering group work	G3
	Encourage students to make and justify assumptions	G4
Improve course structure and teaching methods	Highlight lecture topics where students are struggling	G5
	Increase number of ABET Outcomes incorporated in course design	G6

These objectives served as guiding principles for Professor Nightingale in designing the OEMP. In our interview, she emphasized her efforts to incorporate a wide range of course topics, strategically aligning the application of these concepts with the OEMP to directly coincide with corresponding lectures. This synchronized timing allows Professor Nightingale to pinpoint areas of difficulty for students by highlighting conceptual struggles as they engage with course concepts on the OEMP which enables her to adapt her teaching methods during lectures. By revisiting challenging topics and clarifying conceptual ideas, Professor Nightingale ensures that students gain a comprehensive understanding of each concept.

B. *Scaffolding and Engineering Judgment (RQ1)*

OEMP Part 1 and 2 are used to address the first research question about which aspects of the OEMP scaffolding are productive or prohibitive towards students engaging in engineering judgment. These parts require more decision and assumption making than the succeeding parts and provide students ample freedom in choosing how to approach the problem. From our analysis of data source 2 we expected students to use engineering judgment when working through tasks 1.1, 1.2, 1.4, and 2.1 - 2.3. The written OEMP scaffolding for each task will be presented in the following text to highlight how use of engineering judgment is scaffolded into the problem, as well as whether that scaffolding was productive or prohibitive in getting students to engage with engineering judgment.

For individual tasks, Table 3 presents the specific planned scaffolding found in the written OEMP document alongside the engineering judgments that the student group made for each part. The fourth column also includes which professor goals are achieved by the combination of written scaffolding and elicited judgments. The succeeding text discusses the relationship between how and why that specific scaffolding may have led to students eliciting those specific judgments, as well as how we selected which professor goals were achieved by each set of scaffolding and corresponding student judgment.

Table 3: Scaffolding Analysis Results

Task Number	**Specific Written Scaffolding (Data Pool #2)**	**Elicited Engineering Judgment (see Data Pool #3 for Taxonomy)**	**Professor Goal (Data Pool #1)**
1.1: Determine Pool Lift Range of Motion	As a team, discuss reasonable ranges for the Pool Lift Dimensions with *functionality* in mind. Consider the user, pool constraints, as well as potential guidelines and standards for pool lifts	E3 E4 E7	G2 G4
1.2: Assign User Weight Limit	Determine user's recommended weight limit for your design and justify your selection	E3	G3
1.4: Assign Lift Arm and Assembly Member Dimensions	Discuss reasonable ranges with *functionality* in mind… Will the device be capable of functioning as desired.. How might the amount of force required vary based on position of hinge G? Come to a consensus after discussing these considerations and use geometry to justify the feasibility of your design.	E3 E9 (3x)	G2 G3
2.2: Static Analysis of System at Worst Case	Perform a Static Equilibrium analysis for your team's agreed upon worst-case positions. FBDs and equations should be created and analyzed in 2D.	E3 (2x) E6	G2 G3 G4
2.3: Design the base geometry	Consider the following: how much concrete will you need, how large an area is required to house the concrete, and where will you position the concrete within the base?	E2 (3x) E3 E9 E10	G2 G3 G4

Task 1.1: Determine Pool Lift Range of Motion

In Task 1.1, students were asked to determine the height that the pool lift is capable of raising and lowering, with specific instructions to "Consider the functionality of the device when lowering and raising a person" and "Consider the user, pool constraints, as well as potential guidelines and standards for pool lifts" [OEMP Spring 2021 version]. This scaffolding effectively guided students towards real-world considerations, reflected in their use of engineering judgments E3 "Assumption makes the model more realistic, accurate, representative, or typical based on the student's research or experimentation for the class", E4 "Assumption makes the model more realistic, accurate, representative, or typical based on the student's personal lived experience outside of the classroom", and E7 "assessing the reasonableness of assumption that the student made."

We attribute student use of E3 to the specific scaffolding that prompts students to search for guidelines and standards, as this is likely the reason why students decided to look into outside research for assistance in choosing reasonable values. This specific scaffolding is also effective in allowing students to retain agency in their own work as they are prompted to consider guidelines and standards, but traditional research is not necessarily required. We attribute E4 and E7 to the piece of scaffolding regarding functionality of the pool lift, as each of these instances of engineering judgment involve the students discussing what a "typical" pool lift would look like, and also assessing whether their dimensions would be feasible for their lift. Overall, we determine these pieces of scaffolding to be productive in engaging students with engineering judgment.

This scaffolding is also effective in addressing professor goal G2 of exposing students to real world problems, as students are given the agency to choose their own problem-solving approach (choosing whether to incorporate outside research). Professor goal G4, encouraging students to make and justify assumptions, is also achieved as students elicited E7, assessing the reasonableness of an assumption made for the chosen raising and lowering heights.

Task 1.2: Assign User Weight Limit

This task asks students to assign a recommended user weight limit for their pool lift model, specifically stating, "Determine the user's recommended weight limit for your design…Justify your selection." As this task succeeds 1.1, we feel students are influenced by the same scaffolding as before, and we recorded one instance of E3 as students again look towards a resource in guiding their selection for weight. Additionally, the wording to "justify your selection" likely encouraged students to seek an outside source to ensure their weight limit was reasonable without telling them directly. By requiring students to justify their answer, we think the professor greatly reduced the likelihood of students choosing an arbitrary weight. This is reflected in the group transcript as students did not use E1 - "Making an assumption with no justification" during their weight selection. This scaffolding is effective in achieving professor goal G3 of introducing students to engineering group work, as the statement "Come to a consensus" encouraged the students to have an in-depth discussion about a reasonable weight limit.

Task 1.4: Assign Lift Arm and Assembly Member Dimensions

This task asks students to assign dimensions to the lift arm and assembly members. The specific scaffolding in the task includes conceptual questions intended to guide students' thoughts:

> As a team, discuss <u>reasonable ranges</u> for the Pool Lift dimensions with functionality in mind. Begin refining your dimensions while considering the following questions. Will the device be capable of <u>functioning as desired</u> given your selected dimensions? How might the amount of force required to raise and lower the user vary based on the position of hinge G with respect to B?

These guiding questions, similar to those included for tasks 1.1 and 1.2, again promoted judgment E3 by encouraging students to use "reasonable ranges" and consider "functionality," leading to students seeking outside resources. In this specific instance, a student watched videos on YouTube to better understand reasonable proportioning of dimensions for pool lifts. Students also used E9, "Using a technology tool to help with analysis or computation," three times as they incorporated SolidWorks modeling, Microsoft Excel, and MATLAB when performing necessary calculations to geometrically justify dimensions. Our analysis of 1.4 is consistent with those found in 1.1 and 1.2 as we conclude this open-ended, guiding scaffolding to be productive in promoting the use of engineering judgment while giving students enough autonomy in choosing which specific member dimensions to assume and which to mathematically solve for. This again achieves professor goals G2, G3, and G4.

Task 2.2: Static Analysis of System at Worst Case

Task 2.2 requires students to perform a static analysis of the pool lift, specifically at a worst-case tipping scenario. This prompts students to identify, with their group, when this worst-case scenario will occur, and the group transcripts showed use of judgment E6 "Assumption models what the student thinks is the worst-case scenario" while working through this task. We think this scaffolding, while straightforward, does engage students in engineering judgment in a way that traditional homework frequently falls short- typically, students are provided with a diagram showing a specific state at which they must analyze a system, but little thought is put into why students are analyzing that particular state. This scaffolding allows students to delve into the importance of identifying a worst-case state, which is a useful tool in the professional engineering world. This task's scaffolding accomplishes professor goals G2, G3, and G4 as students choose their own worst-case in a group setting, and must justify their choice to each other and in their written submission.

Task 2.3 Design the Base Geometry

This task requires students to design all features of the base geometry, including its dimensions, weight, location of the base's center of gravity, and the length of horizontal stabilizing arms. Specific written scaffolding includes a series of prompting questions as denoted in Table 2. Students use several engineering judgments while working through this task, including E2, E3, E9, and E10. At this point of the problem, the group transcript shows that students began considering real-world constraints not mentioned or scaffolded into this part. Students used judgment E2 "Assumption considers the user, client, or manufacturer" when they discussed the need to leave room in the base for the pool lift's electrical components such that the manufacturers could store them in the base. We feel that the overall scaffolding from previous tasks had a lasting impact on student's continued view of relating the OEMP to a real-world engineering problem, leading students to continue using judgments E3 and E9, as well as incorporating E10 "Overriding a calculated answer considering the user, client, manufacturer, or safety" when the students decide to add a few inches onto their calculated base dimensions to ensure the concrete will fit. This section again accomplishes professor goals G2, G3, and G4, each pertaining to preparing students for real-world engineering.

C. *Scaffolding and Student Engagement with Course Material (RQ2)*

OEMP Part 3 and 4 are used to address the second research question that states which aspects of the OEMP scaffolding are productive or prohibitive towards students engaging with course concepts. These parts require very little engineering judgment and focus intently on students' ability to integrate and apply various course concepts to a real-world problem. Specifically, Tasks 3.2 - 3.6 and 4.1 - 4.3 involve the application of course concepts. The written OEMP scaffolding for each task will be presented in the following text to highlight how the problem scaffolding encourages students to incorporate different course concepts, as well as whether that scaffolding was productive or prohibitive in guiding students to engage with course material.

Table 3: Statics Anaylsis Results

Task Number	**Written Scaffolding (Data Source #2)**	**Evidence of Task Completion in Group Transcript (Data Source #3)**	**Professor Goals (Data Source #1)**
3.2: Create FBD	As a group, redraw the combination of FBD(s) your group plans to use in order to solve for the unknown joint reactions	✓	G1 G3
3.3: Write Equilibrium Equations	Write a set of equilibrium equations for each FBD you have drawn. Be sure to label all external forces and relevant dimensions	✓	G1
3.4: Solve Equilibrium Equations	Solve for the reactions between the Portable Pool Lift and the ground (i.e. normal forces at the wheels)	✓	G1
3.5: Identify Two-Force Members	Make note of any two-force members. Are the two-force members in tension or compression for each scenario?	✓	G1
3.6: Show Greatest Force on Member ABC and Hydraulic Cylinder GH	Be sure to consider the *resultant force* each joint	No evidence found	Not Applicable
4.1: Determine How to Model the Support at Point A, and Solve For Support Reactions	Consider the type of support point A could be modeled by. Solve for the support reactions at A.	✓	Not Applicable

Task 3.2 - 3.5: Creating a Free-Body Diagram (3.2); Writing (3.3) and Solving (3.4) Corresponding Equilibrium Equations; Identifying Two-Force Members (3.5)

These tasks from Part 3 require students to draw a free body diagram of relevant pool lift members, then write and solve the corresponding equilibrium equations to find each joint reaction. These tasks draw on students' abilities to create FBDs for a frame/machine problem, as well as their ability to use the method of joints or sections to solve the equations. Additionally, to make the problem solvable, students must decide which members can be denoted as two-force members.

The specific written scaffolding is intentional in breaking this computation into smaller, more achievable steps. Alternatively, the problem could have only asked students to compute all joint reactions, rather than breaking this into four individual tasks of drawing the diagrams, writing equilibrium equations, solving equations for joint reactions, and finally noting two-force members. We think this broken-down scaffolding was effective in showing students the anticipated work-flow for applying frame and machine concepts to a real world problem. Due to the complexity of the pool lift as compared to a typical frame/machine homework problem, this structure seemed to be effective in making the statics work more achievable for the student group. This scaffolding effectively incorporates professor goal G1 of reinforcing what students are learning in class and G3 of introducing students to engineering group work as the student group spends ample time discussing the underlying statics principles needed for these tasks amongst each other.This also allows professor goal G5 to be satisfied, as Professor Nightingale can easily check students' work for each task to note where along the joint computation process students are struggling, if at all.

Task 3.6: Show Greatest Force on Member ABC and Hydraulic Cylinder GH

This task requires students to calculate the greatest force acting on two members of the pool lift. This problem includes scaffolding that explicitly states, "Be sure to consider the **resultant force** at each joint." This scaffolded instruction seems to be prohibitive, as the students make no mention of finding the greatest force. Moreover, they do not make any note of needing to attend office hours, so we presume this scaffold was too closed-ended and did not facilitate thoughtful discussion from students about why the resultant force was needed. It does not seem that students gained any conceptual understanding from this task. Additionally, this scaffolding does not satisfy any professor goals.

Task 4.1: Determine How to Model the Support at Point A, and Solve For Support Reactions

Task 4.1 asks students to determine an appropriate support model for Point A and to solve for the corresponding support reactions, assessing the students' understanding of ways to model supports and solve support reactions. The students spend little time discussing an appropriate support model, and one student simply stated that they need to model it as a fixed support because the professor "pretty much told everybody what it's supposed to be." The professor's interactional scaffold seems to have guided students in choosing a support type. While we can assume that Professor Nightingale used interactional scaffolding to ensure students were fully grasping the application of support-types in the problem, we do not have any data on the professor's interactional scaffolding, and therefore, cannot make an argument as to whether this task's scaffolding is productive or prohibitive.

D. Professor Goals (RQ3)

Improve Students Conceptual Understanding of Material

Professor Nightingale's goal G1 strives to reinforce what students are learning in class. This goal is achieved through the overall structure of the OEMP assignment, which is designed for students to apply lecture concepts on the OEMP directly after they are covered in class. For example, after students are lectured on frames/machines, the students receive Part 3 and begin to work on applying specific frames and machines lecture concepts to their pool lift problem. Also, the written OEMP frequently scaffolds phrases to guide students through the proper thought process when approaching problems. For example, Part 3 featured a list of written questions to guide students through their analysis:

> How do your individual group members analyses and results compare for the joint reactions? Which FBDs did each individual use? How many equilibrium equations were necessary? Are there any two-force members? What constitutes a two-force member?

This type of scaffolding also accomplishes professor goal G1, as it prompts the students to discuss these questions, and therefore the course concepts, amongst each other while working through the problem.

Prepare Students for Real World Engineering

The professor has three goals related to the central idea of preparing students for real world engineering: G2, G3, and G4. Each of these is accomplished through the overall problem design, as well as specific scaffolded tasks. In Parts 1 and 2, students have the freedom to approach the problem in a variety of ways and come up with a range of possible working values, allowing goal G2 "Expose students to real world problems (a problem that has multiple solution paths and does not explicitly give only information needed to solve problem)" to be satisfied as students are encouraged to seek guiding information (rather than being handed all necessary pieces) and there are a range of possible successful dimensions.

Goal G3 "Introduce students to engineering group work" is also satisfied by the problem design and written scaffolding. The professor emphasizes group discussions at least once in each OEMP part, and the group transcript data revealed a significant amount of discussion among peers about conceptual understandings and feasibility of different solutions presented by different students.

Goal G4 "Encourage Students to Make and Justify Assumptions" is satisfied by the requirement that students assume certain values/dimensions/weights in order to move forward with the problem. For example, when determining an appropriate user weight, students really have no basis for using an equation to calculate an answer. Rather, they are guided towards pool lift standards and guidelines to help them make and justify an assumption for user weight.

Improve Course Structure and Teaching Methods

Professor goals G5 and G6 pertain to the overall structure and design of the course and are not directly measurable through the assignment scaffolding or student data. However, during our interview with Professor Nightingale, she communicated that Goal G5 "Highlight lecture topics where students are struggling" has been satisfied as she is able to look at student work, analyze any frequent mistakes, and restructure lectures to clarify class-wide conceptual misunderstandings. The OEMP presents a unique opportunity for this type of insight as Professor Nightingale can see if students have a true conceptual grasp of course material. In contrast, traditional engineering homework problems can often be completed with a superficial conceptual understanding if students simply memorize the application of equations. Goal G6 "Increase number of ABET Outcomes incorporated in course design" is also satisfied through the addition of the OEMP as the problem allows Professor Nightingale to satisfy several ABET outcomes.

V. Implication/conclusion

A. Implications

We determined that open-ended scaffolding statements that give students agency in their workflow are effective in engaging students with both engineering judgment and meaningful discussion about course concepts. Additionally, requiring students to justify their assumptions effectively guides them toward using an engineering mindset. Depending on the task, a more detailed breakdown of the expected workflow can also be productive in guiding students through an unfamiliar, real-world application of course material. However, scaffolding that is too direct or close-ended can limit the need for students to engage meaningfully with course concepts. Overall, we found that the pool lift OEMP, which emphasizes group work and real-world application of course concepts, satisfies several ABET Outcomes and is beneficial for undergraduate engineering course design. When scaffolded effectively, an OEMP provides undergraduate students with a workspace to develop an engineering mindset and begin to elicit engineering judgments, thus better preparing them for the challenges they will face in the engineering industry.

B. *Future Work*

Our future work is focused on designing a new study to collect data on the interactional scaffolding between Professor Nightingale and students. The group transcript includes several instances where students discuss attending office hours to get assistance with various tasks on the OEMP, and we conclude that these types of interactional scaffolds played a large role in the successful student completion of the project. For example, we did not see instances in the group transcript of students' struggling as they frequently went to office hours for assistance with difficult tasks. This interactional scaffolding appears to assist students through difficult parts of the project where written scaffolding is too vague. Additionally, our plans involve studying a larger sample of students to improve the breadth of our findings and enhance the validity of our conclusions about the pool lift OEMP's scaffolding. By gathering data on the interactions between the professor and students regarding the OEMP, we can gain a more comprehensive understanding of the full range of scaffolding that is integrated into this problem and communicate these findings to assist other professors who may be interested in writing, and therefore scaffolding, an ill-defined engineering problem.

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REFERENCES

[1] N. J. McNeill, E. P. Douglas, M. Koro-Ljungberg, D. J. Therriault, and I. Krause, "Undergraduate Students' Beliefs about Engineering Problem Solving," J. Eng. Educ., vol. 105, no. 4, pp. 560−584, Oct. 2016, doi: 10.1002/jee.20150.

[2] D. Jonassen, J. Strobel, and C. B. Lee, "Everyday Problem Solving in Engineering: Lessons for Engineering Educators," J. Eng. Educ., vol. 95, no. 2, pp. 139–151, Apr. 2006, doi: 10.1002/j.2168-9830.2006.tb00885.x.

[3] D. Jonassen, "Engineers as Problem Solvers," in Cambridge Handbook of Engineering Education Research, A. Johri and B. M. Olds, Eds., New York: Cambridge University Press, 2014, pp. 103–118. doi: 10.1017/CBO9781139013451.009.

[4] E. P. Douglas, M. Koro-Ljungberg, N. J. McNeill, Z. T. Malcolm, and D. J. Therriault, "Moving beyond formulas and fixations: solving open-ended engineering problems," Eur. J. Eng. Educ., vol. 37, no. 6, pp. 627–651, Dec. 2012, doi: 10.1080/03043797.2012.738358.

[5] A. Johnson and J. Swenson, "Open-Ended Modeling Problems in a Sophomore-Level Aerospace Mechanics of Materials Courses," in 2019 ASEE Annual Conference & Exposition Proceedings, Tampa, Florida: ASEE Conferences, Jun. 2019, p. 33146. doi: 10.18260/1-2--33146.

[6] J. Swenson, A. Johnson, T. Chambers, and L. Hirshfield, "Exhibiting Productive Beginnings of Engineering Judgment during Open-Ended Modeling Problems in an Introductory Mechanics of Materials Course," in 2019 ASEE Annual Conference & Exposition Proceedings, Tampa, Florida: ASEE Conferences, Jun. 2019, p. 32786. doi: 10.18260/1-2--32786.

[7] ABET, "Criteria for Accrediting Engineering Programs, 2023 – 2024," Baltimore, E001 12-28-2020, 2024. Accessed: Nov. 10, 2022. [Online]. Available: https://www.abet.org/wp-content/uploads/2021/02/E001-21-22-EAC-Criteria.pdf

[8] J. Swenson, E. Treadway, K. Beranger, and A. Johnson, "'Let Me See What I Could Do': Students' Epistemic Affect When Solving Open-ended, Real-world Problems," in Frontiers in Education Conference (FIE), Lincoln: IEEE, 2021, pp. 1–8.

[9] J. Swenson, E. Treadway, and K. Beranger, "Engineering students' epistemic affect and meta-affect in solving ill-defined problems," J. Eng. Educ., vol. 113, no. 2, pp. 280–307, Apr. 2024, doi: 10.1002/jee.20579.

[10] B. J. Reiser, "Scaffolding Complex Learning: The Mechanisms of Structuring and Problematizing Student Work," J. Learn. Sci., vol. 13, no. 3, pp. 273–304, 2004.

[11] A. F. McKenna, "Adaptive Expertise and Knowledge Fluency in Design and Innovation," in Cambridge Handbook of Engineering Education Research, 1st ed., A. Johri and B. M. Olds, Eds., Cambridge University Press, 2014, pp. 227–242. doi: 10.1017/CBO9781139013451.016.

[12] J. D. Bransford and National Research Council, Eds., How people learn: brain, mind, experience, and school, Expanded ed., 9. print. Washington, DC: National Academy Press, 2000.

[13] R. M. Clark and A. Mahboobin, "Scaffolding to Support Problem-Solving Performance in a Bioengineering Lab—A Case Study," IEEE Trans. Educ., vol. 61, no. 2, pp. 109–118, May 2018, doi: 10.1109/TE.2017.2755601.

[14] B. J. Reiser and I. Tabak, "Scaffolding," in The Cambridge Handbook of the Learning Sciences, 2nd ed., R. K. Sawyer, Ed., Cambridge University Press, 2014, pp. 44–62. doi: 10.1017/CBO9781139519526.005.

[15] A. Johnson and J. Swenson, "Open-Ended Modeling Problems in a Sophomore-Level Aerospace Mechanics of Materials Courses," in 2019 ASEE Annual Conference & Exposition Proceedings, Tampa, Florida: ASEE Conferences, Jun. 2019, p. 33146. doi: 10.18260/1-2--33146.

[16] J. Swenson, A. Johnson, M. Magee, and Caserto, Melissa, "Investigating the Transferability of the Productive Beginnings of Engineering Judgment Framework from Statics to Dynamics," Am. Soc. Eng. Educ. Annu. Conf., pp. 1–17, 2022.

[17] J. E. Swenson et al., "A Taxonomy of Emerging Engineering Modeling Judgment in Undergraduate Engineering Courses," J. Eng. Educ., in revision.

[18] Miel, K., & Swenson, J., & Johnson, A. (2022, August), Emergent Engineering Judgment: Making Assumptions in Engineering Science Homework (Research) Paper presented at 2022 ASEE Annual Conference & Exposition, Minneapolis, MN. 10.18260/1-2--41133

[19] J. Swenson, Developing Knowledge in Engineering Science Courses: Sense-making and epistemologies in undergraduate mechanical engineering homework sessions. Retrieved from Tufts Digital Library Electronic Theses and Dissertations (qz20t471s), 2018.

[20] J. Gainsburg, "Learning to Model in Engineering," Math. Think. Learn., vol. 15, no. 4, pp. 259–290, Oct. 2013, doi: 10.1080/10986065.2013.830947.

[21] J. Gainsburg, "The Mathematical Disposition of Structural Engineers," J. Res. Math. Educ., vol. 38, no. 5, pp. 477–506, 200