The Effect of Assignment Scaffolding on Engineering Judgement

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***Abstract*— This full research-to-practice paper examines the interaction between scaffolding and student thinking on an open-ended problem. The well-defined textbook problems typically assigned as engineering homework are very different from the ill-defined problems professional engineers solve in the workplace. These open-ended, ill-structured problems require professional engineers to employ engineering judgement. Our research team has been investigating how undergraduate engineering students make these judgements when given the opportunity through open-ended problems during their engineering science courses. This study examines how the problem scaffolding, or the design and structure of the homework problem, influences how students engage in engineering judgement while solving ill-defined and open-ended problems. Our results detail how scaffolding supported predictable behaviors, but also resulted in unpredictable engagement in engineering judgement. This unpredictable engagement can then be more explicitly scaffolded in the future to ensure that all students gain this experience.**

Keywords—scaffolding, ill-defined problems, engineering judgement,

I. Introduction

Problem scaffolding, the way the instructor designs and communicates the students' required tasks [1,2], is key to shaping how students engage with, learn from, and successfully complete an activity. This is especially key in more complex and ill-defined tasks, such as engineering "workplace" problems [3,4]. While many of the homework problems currently assigned in engineering science courses, such as statics, fluid mechanics, and dynamics, are well-defined problems from the textbook, these are not the type of problems our engineers will be solving in their future engineering careers.

Our current research project studies *engineering judgement*, a professional engineering practice focused on mathematical modeling [5,6,7]. While undergraduate students cannot demonstrate this practice at the level of a professional engineer, they do have the ability to engage in the *productive beginnings* of engineering judgment [14,15]. In other words, students have the ability to learn from activities that give them some insight into professional engineering judgment and have the ability to engage in behaviors that mirror professional practices at a beginning level, all of which prepares them to further develop their engineering judgment in their future career. In order for students to engage in engineering judgement, they must be assigned open-ended (meaning no correct answer) and ill-defined problems like those engineers solve in the workplace. We have designed problems of this type, called Open-ended Modeling Problems (OEMPs), for students to practice engaging in engineering judgement while constructing a mathematical model of a real world system [8,9]. Due to the open-endedness of these problems, we have found in our current and prior work students "take up" [10] these problems differently and, depending on the solution path they choose, have more or fewer opportunities to engage in engineering judgement [11]. An important next step is to look at how the OEMP scaffolding influences the ways that students engage with the problem and therefore the practices of engineering judgment. By understanding the connection between scaffolding and engineering judgment, we and other instructors can iterate on the OEMPs to better engage students in the productive beginnings of this important professional practice. This project also helps us identify how students unpredictably practice engineering judgement, meaning without prompting. This will not only help us improve the design of OEMP problems, but help us determine other ways engineering judgement can be integrated or currently exists in the engineering curriculum. In this research-to-practice study, we focus on this relationship between the assignment scaffolding and students' experience by asking the following research question: *What aspects of the scaffolding of an open-ended problem elicit students' engagement with the different practices of engineering judgement?*

II. Background

A. Scaffolding

Scaffolding, as defined by McKenna, is "the process by which a teacher, mentor, or more knowledgeable person helps a learner achieve a task that would otherwise be out of reach (p. 232)[1]." In this study, we use scaffolding to include both the design and structure of the homework problem as well as how the professor presents, discusses, and supports the students in their problem solving.

Reiser [2] discusses scaffolding as "a delicate negotiation between providing support and continuing to engage learners actively in the process" (p.275). He discusses how this support is to help learners accomplish the task they are working on and also learn from their efforts so their performance is better on future tasks. In our work, the three learning goals we have within these problems are 1) making sense or developing conceptual knowledge, 2) using mathematical models, and 3) making judgments. For the purposes of this study, we focus solely on making judgements.

B. *Engineering Judgement*

Our study examines the relationship between scaffolding and students' engagement in engineering judgment. Engineering judgement, as defined by Gainsburg [5], is using "judgement to make a final call on the reasonableness of the analysis or design" (p.287). In her paper, Gainsburg identified different categories of engineering judgement. In our forthcoming/current and prior work [8,12], we have identified the productive beginnings of the following categories:

EJ1. Determining what is a good or precise enough calculation or estimation

EJ2. Making and assessing assumptions or simplifications to be the bases of mathematical models

EJ3. Overriding mathematical "proven" results

EJ4. Determining appropriate uses of technology tools

EJ5. Discretizing (grouping elements to reduce the number of types to be designed)

EJ6. Determining what elements or conditions were "typical" (representative) for the structure

EJ7. Choosing a property or value to make the product better for a user, client, or manufacturer.

The first six categories are taken verbatim from Gainsburg ([5],pp. 486-487). The seventh category came out of our analysis of the productive beginnings of engineering judgement [12], detailed in the Methods section. We believe this new category emerged in our work as Gainsburg's study, which focused on structural engineers, did not involve consumer products. However, our OEMPs did involve consumer products, and the students in our studies are aerospace, mechanical, and engineering science students who were concurrently or previously enrolled in design courses as they were participating in our study.

III. METHODS

A. *OEMP Structure*

An OEMP about the iWalk 2.0 Hands Free Crutch device (Figure 1) was assigned at two universities during the 2019-2020 academic year—Blue University and Maroon University. Blue University is a small private university located in the northeastern United States. 75 students were enrolled in two sections of a statics course in the mechanical engineering department. This first version of the iWalk OEMP was assigned as one singular problem and was due during the eighth week of the course. Students at Blue University also had access to a physical model of the iWalk device and could visit the instructor's office to measure, examine, or use the device. Maroon University is a small private university located in the southern United States. 38 students were enrolled in two sections of a statics course in the engineering science department. This second version of the iWalk OEMP had two parts—an individual assignment and a follow-on group project that replaced an exam when the Covid-19 pandemic moved classes online. The group project also had an initial task for students to complete individually. Students at Maroon University did not have access to a physical model of the iWalk.

Fig. 1 The iWalk 2.0 Hands-free Crutch device (left) and the 2D diagram provided by the professor (right).

Instructors at the two universities assigned similar versions of the iWalk OEMP with slight variances in the scaffolding. The iWalk problem scaffolding can be broken down into three distinct steps: 1) creating free body diagrams, 2) calculating the diameter and selecting the material, and 3) assessing the reasonableness of the calculated answer.

1) *Creating the free body diagram*

The first task of the OEMP asks students to draw free-body diagrams (FBDs) of the entire iWalk system, and then of each member individually. In order to accomplish this task, students must make many assumptions including the stance of gait, the amount of weight of the person on the device, the number and direction of the forces, the dimensions of the device, and the connection at joint B (see Figure 1 above). The problem asks students to list any assumptions or simplifications they made while drawing the free body diagram.

2) *Calculating the diameter and selecting the material*

The second task of the OEMP asks students to solve for the axial load on member AB (see Figure 1 above) and to determine the diameter and material of the member. There are two ways to accomplish this task—students can choose the material and calculate the diameter based on their chosen material's yield strength, or they can choose a diameter and find a material that has a satisfactory yield strength. Students are asked to justify their answer with either method. A breakdown of how Blue University students did this work can be seen in our prior work [11].

3) *Assessing the Reasonableness*

The last task of the OEMP asks students "Is the size of the bar [member AB] you found physically reasonable? Why or why not?" This reflection prompt was not an initial feature of OEMP scaffolding but was added after our analysis of the first interviews [8] in order that all students, just not the ones who participate in the interviews, can examine and assess their work. A previous analysis of Blue University students' judgements of reasonableness and justifications of those decisions can be found in our prior work [11].

The iWalk OEMPs assigned at Blue University and Maroon University were very similar; however, there were some differences in the way the two instructors presented their respective OEMP. The problem provided by Maroon University was more structured than the problem given by Blue University, with a more defined format to solve the problem as well as a specific way for students to identify their own assumptions within their work. The Maroon University OEMP also mentioned the use of safety factors and worst-case scenario situations. The problem given by Blue University left some more room for interpretation, but also asked students to think about the effects of additional forces, and even asked students to test the model in a different gait stance to see how the model changed. Furthermore, there were differences in the depth to which students discussed the OEMP with their peers. At both universities, students all completed the above three steps individually and then met with their peers to compare their individual work and to re-do each of the steps, thereby creating a group report that was better than any one student's individual work. Students at Blue University completed this group work in-class during one course meeting, while students at Maroon University spent a longer time outside of class working on this group project.

B. Data Collection

The research protocol was approved by the institutional review boards at Blue University, Maroon University, and the researcher's institution, the University at Buffalo. At each university, students were asked to consent to an interviews after they submitted their OEMP. Of the students who consented, students were randomly selected to participate in the interviews. The only exception to this random selection was if a few students of one gender consented. In this case, our research protocol allowed us to purposefully select students of that gender, and then randomly select students of the other gender. Not all students who consented to an interview were selected, and students who participated in an interview received no compensation.

Data was collected from eleven different student interviews, four with students from Blue University and seven with students from Maroon University. The interviews were semi-structured and conducted by the first author. The interviews covered four general topics: the students were asked to 1) recall the process by which they came to their answer on the OEMP; 2) evaluate whether their final product was accurate enough, a sufficient approximation to reality, and the best model; 3) think about the nature of the OEMP by comparing it to other assignments in the course and their conception of a practicing engineer's tasks; and 4) briefly discuss their background and prior experiences in engineering. Interviews were recorded using an online conferencing system and then transcribed for analysis. Students at Maroon University were asked to select their own pseudonym, all of which are used in this paper. Students at Blue University were not asked to select their own pseudonym, and in this paper are referred to by number so as to not suggest any identifying information about the students.

C. Data Analysis

Two undergraduate research assistants, the second author and another student, used a semi-grounded approach [13] using Gainsburg's [5] list of engineering judgements as a guide to open-code the interviews. Both students read through each of the transcripts and identified utterances that showed evidence of engineering judgement. These utterances were grouped together in a table with similar utterances, forming a draft codebook. As the two undergraduates identified fringe utterances, or utterances they were unsure how to code, we discussed them in laboratory meetings and used these discussions to clarify our code book. The final codes, based off of Gainsburg's [5] list but modified based on undergraduate engineering students' abilities, form a framework of the seven productive beginnings of engineering judgement, EJ1-7, as are seen in Section II.B. The third author then reviewed all the utterances identified by the two undergraduate students and re-coded them. This process produced the 193 utterances we use as data for this study. Further explanation of our productive beginnings of engineering judgement framework will be published in a forthcoming publication [12].

For this paper, we took the 193 utterances displaying a category of engineering judgment and then separated them by university and student. For each utterance, the second author referred to the interview transcript to identify the question that led to the utterance, and referred to the assignment to identify the step of the OEMP (creating free body diagrams, calculating the diameter and selecting the material, and assessing the reasonableness of the calculated answer) that the utterance addressed. The interview question was noted in order to determine if the utterance was responding to a question or reflecting on how the student completed the OEMP. This coding was again checked with the entire lab group, including the first and third authors, to help identify codes when there were unclear definitions for a particular utterance's connection to the problem. Lastly, we looked across students to determine which step of the problem in which each of the seven categories of engineering judgment were most-commonly found. These results are presented in the next section.

IV. RESULTS

In this section we present how students engaged in engineering judgment in predictable (i.e. scaffolding-driven) and unpredictable (i.e. student-driven) ways for each of the three major steps of the OEMP: 1) creating free body diagrams, 2) calculating the diameter and selecting the material, and 3) assessing the reasonableness of the calculated answer. The predictable exhibitions of engineering judgment were explicitly or implicitly scaffolded by the assignment. The unpredictable exhibitions of engineering judgment were not scaffolded; instead, students chose on their own to use their engineering judgment in a way to make solving the problem easier, create a solution that was more realistic, or prioritize usability or manufacturability. In this analysis we focus on commonalities in the ways that students at Maroon University and Blue University engaged in the productive beginnings of engineering judgment in response to the assignment scaffolding. At both

TABLE I. NUMBER OF UTTERANCE IDENTIFIED FOR EACH CATEGORY OF ENGINEERING JUDGEMENT FOR EACH STUDENT

	Predictable Categories		Unpredictable Categories				
	EJ1	**EJ2**	**EJ3**	**EJ4**	**EJ5**	**EJ6**	**EJ7**
Maroon University							
Adam	2	9	1	0	1	5	1
Lane	4	9	3	0	1	6	3
Larry	4	5	2	0	2	3	1
Cristina	1	4	0	0	0	11	2
Dylan	0	11	1	1	0	5	3
Geoffrey	0	4	0	0	2	3	1
Rich	0	2	4	0	1	0	2
Blue University							
Student 1	6	5	0	0	0	5	1
Student 2	6	11	0	0	0	4	2
Student 3	4	3	0	2	0	8	4
Student 4	0	5	0	0	0	9	0

universities students were asked to perform the same analyses of the iWalk; the primary difference was the degree to which students worked with their peers after completing the OEMP individually.

Our initial identification of 195 utterances of engineering judgement can be found in Table I. Of these utterances, 95 were predictable and 100 were unpredictable. In Sections IV, A – C we present the step of the OEMP scaffolding where we most frequently saw each specific category of engineering judgement, but that does not mean every utterance identified was found to be associated exclusively with that step of the problem. For example, we mostly found instances of choosing a property or value to make the product better (EJ7) while students were calculating the diameter and selecting the material (step 2). Yet, at least two utterances were found while discussing making assumptions to create the free body diagram and one was found when discussing justifying the reasonableness. Similarly, determining what element or conditions were "typical" for the structure was discussed throughout all three steps of the OEMP. This reinforces the importance of giving students agency [16,17], or "freedom" as our participants describe it [10], to allow for the unscaffolded and authentic practice of engineering judgement.

A. Step 1. Creating the Free Body Diagram

This first step of the OEMP explicitly asked students to make assumptions (EJ2) in order to find the values of forces, moments, and dimensions of the iWalk model, and we found evidence of students doing this an average of six times in each interview. Students often made assumptions and held to them throughout the entire problem-solving process. However, we also saw students make assumptions in response to problems in their model caused by prior assumptions. Specifically, if joint B was assumed to be a pinned joint that could freely rotate, the problem was solvable with the knowledge the students had at the time. But, if joint B was assumed to be a welded joint (a more realistic assumption), the problem was statically indeterminate and therefore unsolvable. Some students started by assuming joint B was pinned and holding to that assumption. Other students started by assuming joint B was welded but then had to reassess their assumptions later. As Adam, a student at Maroon University, said,

> At first, I tried doing a welded joint so where there would be a moment along with it, but then every way I tried going about that, everything became statically indeterminate because there were too many unknowns. So I ended up going with a pin joint—that way I wouldn't have that moment and I could figure out, not all of the forces, but at least most of them.

While EJ2 was scaffolded into this step of the OEMP, students exhibited other unpredictable categories of engineering judgment that were student-driven and not scaffolded explicitly or implicitly. In this step of the OEMP, students frequently determined what conditions were typical (EJ6) in order to make the model representative of the real world even though students were never explicitly asked to do so. For example, one student from Maroon University, Cristina, discussed how she measured her family members' calf muscle sizes in order to make the dimensions used in her model realistic. She said, "Calves just differ a lot but like I still measure like the length 'cause I just wanted an idea for it." Another student from Maroon University, Larry, discussed how he looked up anthropometric data from the internet, saying, "Obviously, I looked up the average height of a person and then I looked up their average how long their leg would be, and it's different depending if the user's a female or male. But, I think I chose male."

Students were also not explicitly asked to use technology tools (EJ4) or discretize (EJ5) but these assumptions were used in association with this part of the problem three and seven times respectively. For example, a student at Maroon University, Dylan, said one of his group members "analyzed individual pixels of the image [of the iWalk] in order to determine an approximation for each length of the member based on the average, based on the length of a person length." Students were not expected to use image software to count pixels and determine the dimensions of the iWalk, but Dylan's group member determined this was an appropriate use of a technology tool (EJ4) on his own. Larry described a time when he "applied the person's weight of their leg and foot as one," thereby grouping the weight of these separate body parts together to make the modeling easier (discretization, EJ5).

B. Step 2. Calculating the Diameter and Selecting the Material

In the second step of the OEMP students were asked to determine the diameter and material of member AB in the iWalk (Figure 1). We saw a number of students determining what conditions were typical (EJ6) and choosing a property or value to make the product better for a user, client, or manufacturer (EJ7). Within EJ7, students considered the material cost (e.g. "This could not profitably be made with titanium. That would be way too expensive."), ease of procurement (e.g. "And the aluminum at least to my knowledge is a decent bit accessible and cheaper than steel, so just based off of economic purposes which I know it's not part of the problem but I think that way just in general."), weight (e.g. "I thought that a lighter AB member would be better because the entire iWalk would just weigh less."), and aesthetics (e.g. "So I ended up choosing like, brass copper for aesthetics and functionality"). All of these instances of engineering judgment were unpredictable in that they were not explicitly or implicitly scaffolded, but they were seen frequently in the student interview data.

C. Step 3. Assessing the Reasonableness

In the third step of the OEMP students were explicitly asked to assess the reasonableness of their calculated results, which is the first category of engineering judgment. Therefore, all students predictably exhibited EJ1. For example, as Student 3 from Blue University said:

> When that happens the values that are getting– that I was getting was not realistic for me. Especially because I've seen the material or the object already. This is a very small radius for the size that I've seen.

More surprising was how students unpredictably discussed overriding their calculated result (EJ3) by reporting a diameter for member AB that was larger than the value that they calculated. We saw this discussed eleven times, only by students at Maroon University. As Lane from Maroon University told the first author,

> We got a diameter about 1/20 of an inch, so, um...we knew it would support this load at 1/20 of an inch, but we didn't really think that that was the best diameter, again, because of the balance issues. So, then we went ahead and kind of assumed and chose a radius of 1/2 inch.

Admittedly, the assumptions and simplifications that students have to make to solve this OEMP often led them to unreasonable calculations for the diameter of member AB. In other words, Lane's calculation of a 1/20-inch diameter is not necessarily the result of a math error. A number of students just reported the calculated diameter and discussed that the value was too low, which is all that the OEMP scaffolding required. However, some students, like Lane, did not just report a number they felt was unreasonable; instead, they decided on their own to increase the number.

Analyses of the interview data do not suggest why students at Blue University did not demonstrate EJ3, while students at Maroon University did. However, the Maroon University assignment explicitly stated, "Keep in mind that the end goal of this model is the design of member AB: when in doubt, you might consider designing for a worst-case scenario or with a safety factor." This text, which was not included on Blue University's OEMP assignment, may have let students know that they did not necessarily have to hold fast to their calculated results. Instead, they could "consider designing […] with a safety factor" by overriding the calculated results and reporting a larger diameter. Blue University students were not prohibited from overriding their calculated results, but their assignment also didn't suggest they could do this.

V. DISCUSSION

The goal of OEMPs is to engage students in the productive beginnings of engineering judgment, and it is important to understand what aspects of problem scaffolding lead to this. The results across all three steps of the OEMP show that there are three ways in which students' exhibition of engineering judgment interacted with the OEMP scaffolding—the engineering judgment was explicitly, implicitly, or not scaffolded. Two categories of engineering judgment were explicitly scaffolded in the OEMPs, and therefore were predictable in our data. Students were asked to make assumptions and assess the reasonableness of their final answer, and therefore they exhibited EJ2 and EJ1, respectively. The categories of engineering judgment that were implicitly scaffolded were also predictable, although they were harder for the instructors to identify when writing the problem. For example, the instructors knew that making joint B a welded joint would cause the problem to become unsolvable and require the students to reassess this assumption (EJ2). However, the instructors were not sure how the students would encounter this scaffolding. In fact, a number of students chose to make joint B a pinned joint from the beginning and therefore never engage in assessing their assumption.

Lastly, EJ3 (overriding mathematical "proven" results), EJ4 (determining appropriate uses of technology tools), and EJ5 (discretizing) were unpredictable categories of engineering judgment that students employed without explicit or implicit scaffolding. While the instructors expected students to do some degree of discretizing, they did not expect to see students overriding calculations or using technology to solve the problem (as it wasn't necessary). Furthermore, the fact that many students employed EJ7 (choosing a property or value to make the product better for a user, client, or manufacturer) was quite surprising, as this category of engineering judgment was not part of Gainsburg's [5] original framework. Therefore, the instructors had no intention of designing this practice into the OEMPs. However, students' previous and/or concurrent experience with engineering design courses likely led them to consider this aspect of the problem even though it wasn't required.

VI. CONCLUSION

It is encouraging, yet predictable, to see students engaging in the categories of engineering judgment that were explicitly scaffolded into the OEMPs. More important, however, is understanding the unpredictable ways in which students engaged in engineering judgment. As the results show, students chose themselves to employ five categories of engineering judgment (EJ3-7) when solving the OEMP, even though the assignment did not explicitly or implicitly require these practices.

By engaging in the full span of engineering judgment categories, students are getting a more complete learning experience with the productive beginnings of this important professional practice. However, because these unpredictable categories of engineering judgment are student-driven, not all students choose to engage in them. In another paper at this conference, we find that the degree to which students engage with OEMP is related to how they "take up" the problem, which is a student's sense of the goals of the OEMP activity [10]. Some students take up the OEMP as a homework problem, and we believe these students primarily engage in the predictable categories of engineering judgment. Other students take up the OEMP as an engineering problem, and we believe these students engage in both the predictable and unpredictable categories of engineering judgment. Future research will explore these connections.

With the current scaffolding of the iWalk OEMP, engagement is not consistent across students because of the nature of the unpredictable categories of engineering judgment. To address this, the OEMP scaffolding could be redesigned in several ways. One way is by explicitly requiring students to engage in more categories of engineering judgment. For example, an instructor using the iWalk OEMP could further extend the OEMP scaffolding to explicitly ask students to take into account the user or the manufacturer (EJ7) when they are choosing the material for member AB of the iWalk. The student could be explicitly asked to choose a material that would keep the iWalk under a certain price point or weight range, or to list design criteria important to a user and/or manufacturer and then choose a material based on those criteria.

An instructor could also scaffold the categories of engineering judgment by teaching students about these practices as a part of the OEMP. Cole et al. found that lectures and classroom discussions about modeling improved students' ability to develop and use models as a part of biomedical engineering capstone design [18]. Neither the instructor of Blue University nor Maroon University presented the productive beginnings of engineering judgment framework to their students, and students did not learn about the framework elsewhere in the curriculum. In the future instructors could present this framework, discuss the ways in which professional engineers use these practices in their work (e.g. from [5]), and explain how the OEMP is designed to engage students in the productive beginnings of these practices. While not a change to the assignment itself, this additional information about the productive beginnings of engineering judgment provides additional scaffolding that may encourage students to engage in more of the categories of engineering judgment.

Lastly, if students are engaging in OEMPs in multiple courses, the scaffolding does not have to be consistent. The OEMPs can have more explicit scaffolding the first time the students complete them, with less scaffolding in subsequent OEMPs. For example, the instructor at Maroon University has given OEMPs to first-year students in Mechanics I (the course in this paper) and sophomore students in Mechanics II [19]. The final OEMP in Mechanics II is a group project in which students chose their own system to analyze, therefore being less scaffolded than the OEMP in Mechanics I. The Maroon University instructor commented on the benefits of introducing OEMPs in subsequent semesters, saying it "helped to build their confidence in attacking ambiguous problems. […] While [students] still needed significant guidance sorting through the implications of different assumptions, they were more comfortable with the idea that a certain modeling decision might result in a more or less complex (and more or less accurate/realistic) model, but that this does not necessarily make one choice correct and another incorrect" [19, p. 8]. In another paper at this conference we also look at how completing OEMPs in both Mechanics I and II had a positive effect on students' epistemic affect [20].

Future research will further investigate the effects that these different changes to the OEMP scaffolding have on students' engagement in the productive beginnings of engineering judgment. While the OEMPs will remain open-ended and ill-defined, the goal is to engage all students equally in this important professional skill during their undergraduate engineering education. Also, by understanding how students unpredictably demonstrate engineering judgment without explicitly being asked, we can begin to look for other assignments and activities that already exist in the curriculum where students are employing the productive beginnings of engineering judgment. For example, the focus of EJ7 on users, clients, and manufacturers suggests a link to design courses. Lastly, we believe these findings are applicable to any open-ended problem, not just OEMPs. We encourage other instructors to notice and reflect on how the scaffolding of their open-ended assignments influences students' learning in predictable and unpredictable ways, and to iterate on their assignments in order to engage all students in the desired learning behaviors.

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