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Consideration for Scaffolding Open-Ended Engineering Problems: Instructor Reflections After Three Years

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***Abstract*—This full research-to-practice paper is a collaboration between researchers and instructors to examine the scaffolding of open-ended problems. Most assigned homework problems are closed-ended with one correct answer and are unlike the ill-defined problems practicing engineers solve in the workplace. To begin bridging this gap, our research team of engineering education researchers and instructors have been designing and implementing ill-defined, open-ended homework problems for the past three years. This study presents instructor reflections on considerations for scaffolding open-ended problems, made after examining survey data from their own students. We present the results in six practices of scaffolding that better support students in their solving of the problems.**

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

I. Introduction

Professional engineers solve complex, ill-defined problems whose solutions are evaluated by non-engineering metrics such as cost, safety, and time [1,2,3]. Engineering students usually only encounter ill-defined problems during first-year challenges, capstone design, and while working on extra-curricular project teams. Rarely do they encounter ill-defined problems in engineering science courses, which typically assign well-defined problems that do not require students to use judgement but apply a specific equation or concept and compute a single correct answer. In order to better prepare students for professional engineering practice and integrate theoretical and real-world knowledge [4] our research team, consisting of engineering education researchers and instructors across six universities, has been assigning students ill-defined problems focused on mathematical modeling that we call Open-ended Modeling Problems (OEMPs). While similar mathematical modeling assignments have been created, assigned, and reported on in literature, such as Model Eliciting Activities (MEAs) [5], our team is specifically studying engineering judgment as an important professional practice that undergraduate students should engage in at a beginning level.

OEMPs have four design elements: students must 1) analyze a real-world object or context, 2) develop a mathematical model of the object or context, 3) practice using modeling techniques recently learned in class, and 4) engage in the productive beginnings of engineering judgement [6,7]. Engineering judgement, a professional engineering practice, is employed when developing mathematical models of systems by making assumptions, deciding when and how to use technology tools, or assessing the reasonableness of a calculated answer [8,9,10].

Our team has focused on particular aspects of the OEMP scaffolding, or the ways in which the instructor(s) help the students achieve a task that would otherwise be out of reach [11]. In our case, we consider scaffolding to be the way the OEMP is presented and worded, the things the instructor says about the activity in class, and the ways students receive support from their instructors, TAs, and classmates. While our prior work on this project has been focused on better understanding the productive beginnings of engineering judgment [6,12,13], this particular study is to collect, analyze, and report the considerations and practices our research team--consisting of researchers and instructors who have designed and implemented OEMPs--has found to be the most productive in scaffolding ill-defined, open-ended problems. We report these findings in this research-to-practice paper in hopes of encouraging more instructors of engineering science courses to include real-world, ill-defined activities and assignments in their courses to aid students in forming connections between their own experience and the course material and to better prepare students for their careers as professional engineers.

Our studies of the assignment scaffolding, such as this paper, have been conducted as action research with tight coupling between the researchers and practitioners [14]. After each semester where an OEMP was assigned in the course, our team has assessed the implementation from the viewpoint of the instructor and the students, then made changes to the assignment scaffolding. For example, after conducting interviews with five students after the first implementation of an OEMP (Yellow University, Fall 2018), we noticed the students benefited from the reflection that occurred during the research interview. For the second implementation (Yellow University, Spring 2019), we added an in-class group discussion for students to compare their models using a worksheet. This in-class assignment was graded solely on participation. In Spring 2020, after the COVID-19 pandemic forced classes to go online, the Maroon University instructor replaced an exam with a group analysis and report portion after the students each did the problem individually. From feedback to the professor, survey data, and interview data, we found this change led to increased conceptual understanding, reduced anxiety about there not being a 'right' answer, and student reflections on approaches and problem solving based on discussions with their peers. Thus, in the Fall 2020 iterations Gold University, Purple University, and Maroon University all had both individual and group parts that were graded. Other iterations like this include the use of grading rubrics, a mid-problem optional feedback from the instructor, and the number of assignments as part of one problem.

This paper represents a reflection and synthesis on the considerations for scaffolding open-ended problems, drawn from three years of research on fifteen OEMPs assigned in nine courses across the country. In this paper, we address the following research question: What beneficial practices do instructors identify for scaffolding an open-ended engineering problem? To answer this question we had the six instructors (Gold University's course had two instructors, one of which was also the instructor at Yellow University) who implemented OEMPs reflect on student end-of-semester survey results from their courses. First, we present the student survey results. Then, we will present common themes from an analysis of the instructors' reflections. Finally, we will synthesize the results to report practices that multiple instructors identified as beneficial to their students' experience while solving the problems. We write about these practices in such a way that they can be implemented by instructors who teach any type of open-ended and ill-defined "workplace" problems. Therefore, our results further the development and implementation of problems that further develop engineering students' mathematical modeling abilities and professional engineering skills.

II. Methods

A. Study Context

A typical OEMP has three distinct parts where students engage in making judgements. Students typically begin by creating a free body or impulse-momentum diagram that requires them to make numerous assumptions such as acting or applied forces and their directions, dimensions, or weather conditions. Then they create their mathematical model and calculate the properties experienced or required by part of the system, which may include a material, diameter, dimensions, shape, material, safety factor or velocity. In most problems, students select values for all but one parameter, which they calculate. Lastly, students gauge if their answer is reasonable or not and reflect on the answer. (For more information about the structure of OEMPs, see [15]). Our other papers, both prior work and at this conference [6,16], detail specifically how we see students practicing engineering judgement in expected and unexpected ways.

Instructors have implemented OEMPs in nine different course offerings at six universities (Table I). These OEMPs have been situated in many different real-world contexts like the iWalk 2.0 Hands-free Crutch, an aircraft in the lobby of the aerospace engineering building, a pool lift, and a slide at a local park (Figure 1). For more details about how the Yellow University instructor implemented a bridge-themed OEMP, see [15], and for more details about how the instructor implemented the Maroon University iWalk-themed OEMP, see [17].

TABLE I. Open-ended Modeling Problem Implementation

University	Semester	Subject	Enrollment	OEMP(s) Assigned	Type of OEMP
Yellow University	Fall 2018	Mechanics of Material	47	2 Bridge Problms	Individual
Yellow University	Spring 2019	Mechanics of Materials	74	2 Airplane Problmems	Individual
Blue University	Fall 2019	Statics	75	iWalk Problem	Individual
Maroon University	Fall 2019	Dynamics	38	Car Crash Problem	Individual
Maroon University	Spring 2020	Statics	43	iWalk Problem	Individual and Group
Maroon University	Fall 2020	Dynamics	36	Car Crash Problem, Student Choice Project	Individual and Group
Purple University	Fall 2020	Statics	134	Pool Lift Problem	Indivdual and Group
Gold University	Fall 2020	Statics & Mechanics of Materials	323	Gondola, Slide, and Airplane Wing Labs	Individual and Group
Orange University	Fall 2020	Human Factors	43	Human Hip Bone Implant	Individual

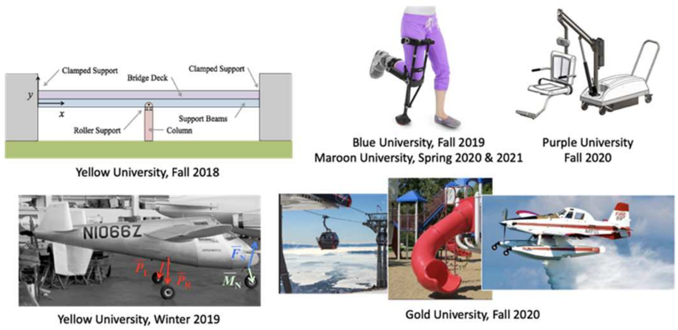

Fig. 1. Select OEMP Themes

B. Data Collection

The focus of this paper is on the OEMP scaffolding, and the primary data source is written reflections made by the instructors as they considered their OEMP implementation(s) and survey data collected from their students. In this section we first present the questions and results of these student surveys, both aggregate and by course, in order to provide context for the instructor reflections. We then describe the method by which these reflections were recorded.

1) *Undergraduate Surveys*

Over a period of three years, the researchers of this project distributed end-of-semester surveys to students in the nine engineering science courses where OEMPs were assigned. The survey distribution resulted in a total of 385 student responses that gauged student feelings and thoughts about the OEMPs. Using Qualtrics, the researchers asked the students roughly 13 questions in each survey. The questions measured a range of student opinions, such as how confident they were in their answers, and how much they enjoyed the OEMP. Students also had the opportunity to respond to an open-ended question that inquired about any general thoughts the students had about the OEMP. Other than an initial question regarding the time it took to complete the OEMP and the last open-ended question, the students rated their responses on a Likert scale, ranging from "Strongly agree" to "Strongly disagree". Author 2 organized the student responses in an Microsoft Excel spreadsheet, conducted a brief analysis for each survey, and then compared the results across all six universities.

In analyzing students' responses to the post-semester survey, the researchers selected four questions that best reflected students' thoughts and feelings toward the OEMPs for our instructors to reflect upon. Figures 2-5 present the responses to these four questions from all nine courses. The N-values for each of the course graphs vary, but in total there were N =385 student responses. The questions that each student responded to are shown on the graph. All students reported their responses via a Likert scale, with options of "Strongly agree", "Agree", "Neutral", "Disagree", or "Strongly disagree".

Because OEMPs are open-ended and quite different from the typical homework problems assigned in an engineering science course, our first consideration is how students respond to the scaffolding of the OEMP. First, we asked whether students knew what was expected of them in an OEMP. This is addressed by the data shown in Figure 2. We chose to present this graph to the instructors so they would reflect both on the results and their own impressions of how students reacted to the scaffolding of the problem.

We also wanted to gauge how the students felt about the work they did, shown in Figure 3. We wanted to ensure the students didn't feel that accomplishing this task was out of reach, based on what they learned in class and the support we and the teaching assistants provided. Therefore, we asked them to express their confidence in their model to gauge if we need to provide more support when asking students to solve the OEMP.

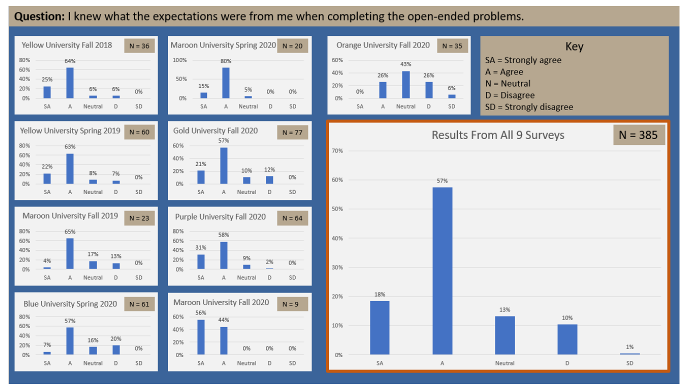

Fig. 2. Students responses to the question 'I knew what the expectations were from me when completing the open-ended problems.'

Fig. 3. Students responses to the question 'I was confident that my models of the -INSERT MODEL – were goo models, given the amount of structures/statics/dynamics knowledge I had at the time.'

The survey also asked a number of questions to determine how students liked the OEMPs. Originally, this was to ensure students were not frustrated or overwhelmed by these problems. Now, as our goal is to integrate more of these problems into higher-level engineering science courses, we continue to collect this data to support that goal. While we simply asked students if they enjoyed the OEMPs, we also asked them to compare the OEMPs to other assignments in order to better contextualize their thoughts. The results, in Figures 4 and 5, show while some students would like more of these problems in their courses, many also are neutral to this idea. We take it as a good sign that some of our students like these problems more than homework problems and want more of them assigned in their classes and wanted to hear instructors reactions to these results and have them reflect on why their students may have felt this way.

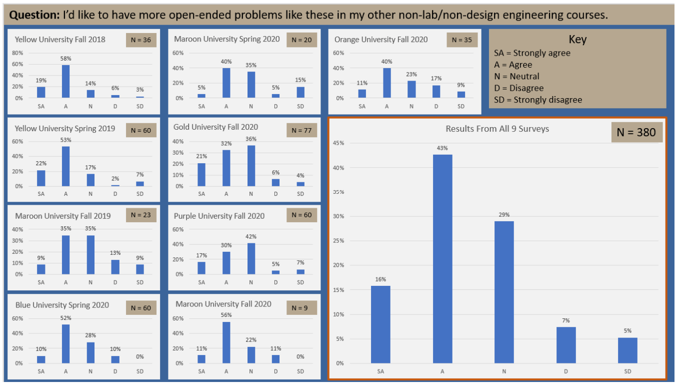

Fig. 4. Student responses to the question 'I'd like to have more open-ended problems like these in my other non-lab/non-design engineering courses.'

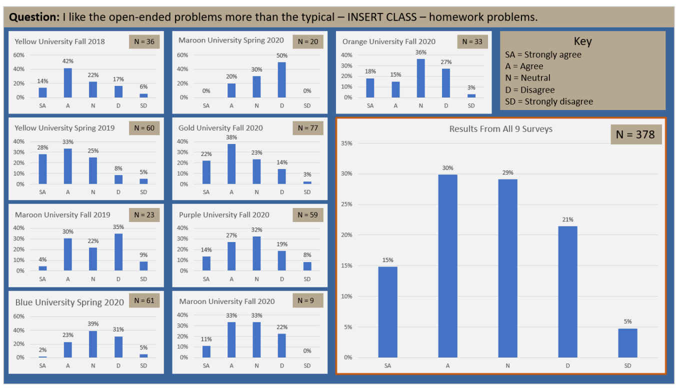

Fig. 5. Student responses to the question 'I like the open-ended problems more than the typical -INSERT CLASS- homework problems.'

2) *Instructor Reflections*

After reviewing the aggregate survey results and selecting the above four survey questions as the most relevant to the assignment scaffolding, the researchers then created an instructor reflection that was distributed to the six instructors who taught the nine OEMPs in Table I. The reflection addressed each instructor's thoughts about the use of the OEMPs in their own courses. The instructor reflections included the aggregate results and the institutional results from the semester(s) the OEMPs were assigned. For instance, the instructor at Maroon University was shown four graphs for each question referencing the student responses: three for each semester an OEMP was assigned and one for the survey representing all student responses across all six universities. The instructors were able to reference these graphs in their responses and were able to see their school's trend compared with the average trend across all six universities.

In total, each instructor was asked five open-ended questions about how students' responses to the four survey questions may have been affected by the specific scaffolding of the OEMP, what the instructor may change in future assignments of the OEMP, and what they considered to be an appropriate ratio of OEMPs to traditional homework assignments. Table II lists the five questions asked of each instructor. The questions posed to the instructors sought to address reasons for their students' responses to the four survey questions, and why their students' responses may have differed from the aggregate response across all universities. The instructor reflection also served as a collection of future considerations for scaffolding an OEMP.

TABLE II. INSTRUCTOR REFLECTION QUESTIONS

Question Number	Question Asked in Instructor Survey
1.0	Presentation of graphs from Figures 2 and 3.
1.1	Using the student responses to the two survey questions above, what do you think went well in your scaffolding of the problem?
1.2	What might you change in the future to better support students in your scaffolding of the problem?
2.0	Referring to the survey responses above (graphs in Figure 4), what aspects of the OEMP(s) do you think make some students want these problems in other courses at your university?
3.1	Referring to the survey responses above (graphs in Figure 5, what aspects of the OEMP(s) do you think make some students like them *more* than the typical homework problems in your course?
3.2	What aspects of the OEMP(s) do you think make some students like them *less* than the typical homework problems?
4.0	What do you think is an appropriate ratio of OEMPs to regular homework problems in an undergraduate engineering course?
5.0	In what ways do you think students learn or retain course concepts differently through completing an OEMP compared to doing regular homework problems?

C. *Data Analysis*

The four questions from the student survey responses were chosen to be included in the instructor reflections. The graph compiling the responses from all nine student surveys, as well as the graph(s) for the specific school where an instructor assigned an OEMP, were shown along with the reflection questions. Author 2 analyzed all instructor responses by taking notes on the themes appearing in each survey. The themes were compared across all six instructors' surveys and general practices, applicable to open-ended problems more broadly, were identified. Author 2 then grouped together the responses that fit under each practice and identified quotes that appeared to exemplify the main idea of the practice.

III. DATA

Six practices in responses that identify consideration for scaffolding an OEMP:

1) Break an open-ended problem into multiple parts
2) Assign an open-ended problem soon after relevant topics or skills are taught in class
3) Frequently reassure students that there are multiple solutions to one problem
4) Provide students multiple opportunities for receiving feedback
5) Recognize that different students may have positive and negative experiences working on open-ended problems in a group
6) Recognize that different students may enjoy and struggle with the open-endedness of the problems

Each practice header is followed by quotes from the reflections that represent the ideas shared by multiple instructors, as well as descriptions of each quote.

A. Practice 1: Break an open-ended problem into multiple parts

When the instructors reflected on their scaffolding of the OEMP, multiple instructors mentioned how gradually assigning parts of the OEMP over a period of several weeks seemed to increase their students' self-confidence in their work. One instructor, after having assigned multiple OEMPs, noted the change in the students' confidence after breaking the assignment into multiple parts:

> In Fall 2019 when I assigned my first OEMP, I gave it as a monolithic homework problem that was different than anything else my students had seen, and I had not developed the grading rubrics in advance of assigning the problem – which is reflected in the relatively lower student confidence in understanding what was expected of them that semester compared to the following semesters [where she assigned OEMPs in multiple parts]. (Maroon University)

Similarly, another instructor attributed the confidence he saw in his students to assigning multiple OEMPs in one semester:

> I think having the first OEMP under their belt – and seeing how we graded it – helped give students more confidence. (Gold University Instructor 1)

B. Practice 2:Assign an OEMP soon after relevant topics or skills are taught in class

Beyond simply breaking an OEMP into parts, instructors remarked how assigning each part after relevant topics were just covered in class greatly benefitted the students. One instructor claimed that this practice increased her students' confidence:

> The OEMP scaffolding allowed students the opportunity to immediately apply knowledge and modeling skills learned in class to an open-ended engineering problem. I believe this gave students more confidence in their models each week. (Purple University)

The same instructor went on to say that this structure of assigning the OEMP helped students to solve the problem:

> Since the OEMP was divided into parts containing particular aspects of modeling and design that related directly to what was being taught in class the previous week, students had the newly acquired knowledge at the forefront of their minds. (Purple University)

Another instructor noted the confidence his students had after assigning an OEMP directly after topics were covered:

> …I tailored them to the content that students had just learned… So, I think that helped students have confidence that their models were good given their knowledge at the time. (Yellow University)

C. Practice 3: Frequently reassure students that there are multiple solutions to one problem

A hallmark of the OEMPs is that they do not have one correct answer, which can be daunting to students because it is so different from the typical problems they are used to completing in engineering science courses. Instructors frequently mentioned how reassuring their students seemed to ease student apprehension and stress about solving the OEMP. One instructor stated that the practice of reassuring her students seemed to benefit the assignment:

> …more than one student expressed sentiment that this reassurance that there is no correct model helped them to manage their anxiety around approaching the open-endedness of the problem. (Maroon University)

Another instructor thought that his OEMP improved by being clear about the expectations he had for the students while they solved the OEMP:

> …I think something that was good about the scaffolding was how I stressed that students would be graded on their justifications, rather than their final answers. I think that assuaged a lot of students' concerns about this problem being so open-ended. (Yellow University)

When asked what they might change about future OEMP assignments, instructors again discussed the importance of reassuring their students. One instructor went on to say that she would take more time to do just that:

> [I would] emphasize the significance of assumption/simplification/justification in engineering and clearly express that many of the real-world engineering problems are open-ended with no single right answer. (Blue University)

Expressing a similar sentiment, the instructor from Yellow University said that adding a statement in the OEMP instructions may help encourage students even further that they were not being graded on the "correctness" of their answers:

> …I emphasized that students would be graded on their justifications. I don't see that I have that explicitly written in the project description; perhaps that would be something to do. (Yellow University)

D. Practice 4: Provide students multiple opportunities for receiving feedback

In reflecting on what about the OEMPs make some students want to have them in other courses, some instructors cited opportunities for feedback--whether from their peers in group work or by a professor or teaching assistant--seemed to be valued by the students. One instructor claimed that students enjoyed the OEMP because of the opportunity to discuss their work:

> Students seemed to enjoy the group discussion of the open-ended problem with their classmates. (Blue University)

Another instructor generally claimed that his students also enjoyed this aspect:

> I think students appreciated getting detailed feedback on their free body diagrams and modeling strategies. (Gold University Instructor 2)

Furthermore, the instructors also pointed to providing regular opportunities for feedback in future improvements of the

OEMP. One instructor mentioned the idea of allowing students to submit drafts of the OEMP before they submitted the final version:

> My hope is that by looking at drafts where students feel the freedom to simply say "I'm stuck" and giving feedback, I will both help students catch conceptual errors and build their confidence in their modeling skills. (Maroon University)

A second instructor expressed a desire to hold meetings to provide individual feedback to students:

> …scheduling regular opportunities for groups to meet with the instructor or TA would be extremely beneficial in the learning process. This would also help to recognize if or when an individual student or entire group may be falling behind in their overall understanding of the project. (Purple University)

E. Practice 5: Recognize that different students may have positive and negative experiences working on an open-ended problem in a group

While instructors noted that students appreciated feedback from their peers, they also recognized that group work may have helped or hindered students' enjoyment of the OEMP. However, only four universities assigned group OEMPs (see Table I), so this practice is only relevant for those four schools. Several factors may have contributed to this idea, including the individual group experience a student had. One instructor expressed the ambivalence of this idea:

> Adapting OEMPs into group projects is an interesting factor, in that I believe that it makes some students like them more, and others less. (Maroon University)

This same sentiment was felt by another instructor, as well:

> In some cases, the team aspect of the OEMP, caused a dislike for the OEMP if there was a lack of participation within their group. (Purple University)

One instructor claimed that the group aspect of the OEMP caused issues for the students:

> I think that there are some students who are good at math and good at textbook homework problems, and they don't want to be held back by a group. Like, they'd rather just do their work alone and get through the curriculum. So, I could see those students preferring traditional homework. Or, if there was a group where someone didn't show up or put in a good effort, that would mean more work for the other students. So, I could see those students who had to make up for a bad group member preferring traditional, individual homework more. (Gold University Instructor 1)

Interestingly, the same instructor thought the group aspect of the OEMP had the potential to generally improve students' enjoyment of the problem. This again reinforces the duality of this practice:

> …I could see the group aspect being a positive. Students didn't have to do these on their own; they had a group to work with and share the load. (Gold University Instructor 1)

F. Practice 6: Recognize that differencent students may enjoy and struggle with the open-endedness of the problem

The open-endedness of the problems seemed to cause students to both enjoy and struggle with the OEMPs (for students' affective reactions to the problems, see our other paper at this conference). Instructors cited the open-ended as both a reason that students liked the OEMP more than regular homework problems and less than regular homework problems. Many instructors claimed that the OEMPs presented students with a realistic scenario that ultimately made them feel like real engineers. Instructors cited the following reasons for students enjoying the open-endedness of the OEMP:

> The OEMP required students to build on their knowledge from the class to solve a problem that required them to think outside the box and examine the problem from multiple angles. (Orange University)

> The open-ended structure of the OEMP also contributes to a student's enjoyment. (Purple University)

> When students are faced with solving an open-ended problem like the OEMP Pool lift, they are faced with making their own engineering judgments and assumptions rather than being told them. (Purple University)

> Some students enjoy the creativity provided by the open-endedness… (Maroon University)

Contrary to this idea, instructors concluded that students also struggled with the open-endedness of the OEMP, leading to students liking these types of problems less than other homework problems. Multiple instructors noted that the students struggled with not having one correct solution to the OEMP:

> …there is also a great deal of uncertainty and discomfort involved in tackling an OEMP. Students are quite dismayed when I tell them that I will not let them know whether their answers are "correct" since their previous training in technical disciplines (including these classes!) typically teaches them to think of things in black and white. (Maroon University)

> Many students like getting the "right" answer on a single concrete number. The OEMP problems require students to see the "grey" in engineering, and make several assumptions that they might feel uncertain about. (Gold University Instructor 2)

Another practitioner expressed a similar idea, but seemed to think students struggled with the assumption-making aspect of the OEMPs:

Being confused about the "correct" assumptions and simplifications when solving the OEMP as opposed to having all the assumptions and simplifications ready in the typical homework problem. (Blue University)

IV. Discussion

Scaffolding an assignment requires thinking about the tension between guiding a student through a problem and allowing them time to struggle to figure out something for themselves. Instructors implementing any type of open-ended, ill-defined, "workplace" problem must ask themselves questions such as ow much information to provide the students in the problem statement, how to best structure the assignment, and whether to have students work together or individually. Workplace engineering problems do not have scaffolding in place; engineers need to determine how to break the problem into management sub-problems, and they also need to identify the technical skills and content relevant to each sub-problem [2]. In this way, Practices 1 and 2 actually make the OEMPs look less like a workplace problem. However, undergraduate engineering students cannot be expected to solve workplace problems! The purpose of scaffolding is just this--to "help learners succeed in more complex tasks than they could otherwise master" [18, p. 273]. They require scaffolding to be able to solve the problem without becoming too frustrated or anxious. This way, the scaffolding allows other parts of the problem to be ill-defined and helps students to sufficiently engage with the problem so that they can achieve the learning goals.

Our research has focused on engineering science courses, primarily at the lower (first-year and sophomore) levels. And, in all courses except for Dynamics at Maroon University, we focus on courses where students are seeing their first OEMP. And, in many cases, this first OEMP is often students' first open-ended workplace problem. For this reason, our findings represent an initial level of scaffolding that can support students as they just begin to work on ill-defined, open-ended problems. As students gain more experience with OEMPs--or open-ended problems in general--they will require less scaffolding. For example, it is common for students in capstone design courses to be required to break the problem into sub-problems and identify the skills and content needed for each sub-problem on their own, without scaffolding.

V. Conclusion

After three years of implementation and research, our team has found the six practices described above to be effective ways to scaffold open-ended, ill-defined modeling problems in service of developing professional engineering skills in our students. While we have used the scaffolding practices specifically for open-ended modeling problems (OEMPs) that engage students in the productive beginnings of engineering judgment, we believe these practices are applicable to any open-ended engineering problem. These scaffolding practices include better supporting students in the structure of the OEMP, such as assigning multiple parts, giving feedback during checkpoints in the process, and assigning in tandem with recently covered course material. The instructors also feel that they can better support students with stronger communication about the OEMP, by frequently easing student anxiety that the OEMPs do not have one right solution, and providing students with more opportunities for informative feedback. The goal of this project is to provide other instructors with the opportunity to learn from these instructors' experiences in assigning OEMPs and encourage effective implementation for more engineering students.

VI. Implicaitons

In learning from our own considerations for scaffolding OEMPs, other instructors can better prepare their students for careers in engineering through allowing students to learn how to solve more realistic, open-ended problems. This project will continue to refine the OEMPs, as we are always searching for ways to improve them and better support our engineering students. The instructors surveyed in this project have indicated that multiple, smaller OEMP assignments that are assigned soon after relevant course topics have been covered in class may allow students to gradually build up their open-ended problem solving skills. We plan to further explore this type of scaffolding of the OEMP to learn how students are affected by breaking the assignments into more manageable chunks and exploring the impact this may have on students applying these skills later in their undergraduate careers.

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