Open-Ended Modeling Problems in a Sophomore-Level Aerospace Mechanics of Materials Courses

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Abstract

The aerospace curriculum during students' sophomore and junior years is dominated by core technical subjects such mechanics of materials, aerodynamics, propulsion, and controls. Ideally, these *engineering science courses* give students the theoretical background that they can apply in engineering design courses, on student project teams, and as a practicing engineer. However, it can be easy to teach engineering science courses with little connection to the practice of engineering. One way to make the connection between engineering science content and engineering practice is to frame this technical content as mathematical models that describe natural phenomena under certain simplifying assumptions. With this framing, the purpose of engineering science courses shifts from memorizing formulas and applying them to textbook problems, to modeling systems in the real world. This paper describes open-ended modeling problems that the first author developed for his sophomore-level aerospace mechanics of materials course, and assesses students' opinions of these problems.

This paper first presents *engineering judgment about mathematical modeling* as a framework for open-ended modeling problems and then describes the initial set of two open-ended modeling problems that the first author designed around certain aspects of engineering judgment: making assumptions or simplifications, determining appropriate uses of technology tools, discretizing, and determining what elements or conditions were "typical." The paper then investigates student opinions of the open-ended modeling problems through two methods: quantitative analysis of a student survey that shows how students felt about the problems, and qualitative analysis of interviews with five students that probes why students felt they way they did about the problems. Students interviewed found that the open-ended modeling problems related to the real world, helped to teach course concepts, were fun, and made them think. Lastly, this paper concludes by describing modifications the first author made to the open-ended modeling problems for the next semester, as well as our future research plans.

Introduction

During their undergraduate engineering education, aerospace students are given the opportunity to apply the engineering design process to real-world scenarios as a part of cornerstone (i.e. first-year) and capstone (i.e. senior-year) design courses. These design courses are often significant and memorable experiences in students' education where they actually get to design—and maybe even build and fly—an aerospace vehicle. While the importance of design courses in aerospace engineering education is clear, they only make up a small part of the curriculum. After students have an exciting and engaging first-year design experience, students' sophomore and junior years are dominated by core technical subjects such as mechanics of materials, aerodynamics, propulsion, and controls. We define these non-design and non-lab courses (although they may have lab components) as *engineering science courses*. For example, at the University of Michigan, students are required to take 41 credits of engineering science courses (32% of the total credits required for graduation) and only 19 credits of design and laboratory courses (14.8% of total credits). Furthermore, of the 11 current ABET Student Outcomes only one of these, a) an ability to apply knowledge of mathematics, science, and engineering, directly speaks to the content of these engineering science courses [1].

Despite the prominence of engineering science courses in the curriculum, these courses have been studied less in engineering education research than design courses [2]. Ideally, these engineering science courses should give students the theoretical background that they can apply in engineering design courses, on student project teams, and as a practicing engineer. However, it can be easy to teach engineering science courses as applied mathematics courses with little connection to the practice of engineering. Studies have shown that students recognize this and perceive a difference between "workplace problems" and "classroom problems" [3]–[5].

One underlying philosophy that may help students make the connection between engineering science content and engineering practice is to frame the content as mathematical models that describe natural phenomena under certain simplifying assumptions. By reframing engineering science content in this way, students understand the ways in which the content can be applied to analyze and design a system, and the ways in which it cannot be applied due to inherent assumptions that are inaccurate enough to cause problems in the "real world." This focus on modeling is commonly implicit in engineering curricula [6], [7], but research has shown that students best learn modeling practices through their explicit inclusion in the curriculum [8].

One approach to explicitly incorporating mathematical modeling into undergraduate engineering education is through Model-Eliciting Activities [9]. Instead of an instructor-centered pedagogy, Model-Eliciting Activities are student-centered activities in which students work in a small group to develop mathematical models that describe a particular problem. These activities "require students to mathematize (e.g. quantify, organize, dimensionalize) a situation and communicate a model (i.e., process or procedure) that reveals their understanding of the attributes and limitations of the situation" [9, p. 20]. Once students have developed their own mathematical models, instructors can implement two sequential follow-on activities in which students evaluate their models by comparing and contrasting them with existing "conventional" engineering models (called Model-Exploration Activities) or apply or adapt their models, such as by implementing them in code (Model-Adaptation Activities). Instructors can also use Model-Exploration or Model-Adaptation Activities on their own without first doing Model-Eliciting Activities.

This paper describes a sequence of two open-ended modeling problems (OEMPs) that the first author of this paper developed for his sophomore-level aerospace mechanics of materials course at the University of Michigan. The first OEMP is similar to a Model-Eliciting Activity and the second OEMP is similar to a Model-Adaptation Activity. However, one unique aspect of our OEMPs is that we specifically designed them to engage students in productive beginnings of *engineering judgment* [10]. This paper first presents engineering judgment as a framework for open-ended modeling problems, and then describes the initial set of two OEMPs that the first author designed around certain aspects of engineering judgment. These were given to students in the Fall 2018 semester. The paper then investigates student opinions of the OEMPs through two methods: quantitative analysis of a student survey that shows how students felt about the problems, and qualitative analysis of interviews with five students that probes *why* students felt they way they did about the problems. Lastly, this paper concludes by describing modifications the first author made to the OEMPs for the Winter 2019 semester and our future research plans. While this paper focuses on the design of the OEMPs and analysis of student feedback, a companion paper examines the student interviews in more depth to investigate 1) how students chart a solution path and solve an open-ended modeling problem, and 2) how students evaluate their mathematical model and final answer [11].

Engineering Judgment as a Framework for Designing Open-Ended Modeling Problems

Our open-ended modeling problems are purposefully designed to engage students in productive beginnings of *engineering judgment*. Specifically, we use engineering judgment *about mathematical models*, as defined by Gainsburg [10]. In her study of practicing structural engineers at two different firms, she observed the engineers using "judgment to make a final call on the reasonableness of the analysis or design" [10, p. 287]. Gainsburg presents eight categories of engineering judgment [10, p. 486-487]:

1. Determining what is a good or precise enough calculation or estimation
2. Making assumptions or simplifications to be the bases of mathematical models
3. Overriding mathematically "proven" results
4. Determining appropriate uses of technology tools
5. Assigning qualitative factors (e.g. soil type) and applicable conditions for selecting formulas
6. Overriding official building codes
7. Discretizing (grouping elements to reduce the number of types to be designed)
8. Determining what elements or conditions were "typical" (representative) for the structure

These eight categories are not all applicable to our students, such as #6, overriding official building codes. Furthermore, we do not expect students to be able to express engineering judgment at the level of a practicing engineering. However, none of these eight categories are even suggested in closed-ended “plug-and-chug” homework problems. Therefore, the first author designed the open-ended modeling problems to productively engage students in a number of aspects of engineering judgment at a novice level.

Open-Ended Modeling Problems in Fall 2018

In this section, I (the first author of this paper and instructor of the course) describe the design of the two open-ended modeling problems (OEMPs) I gave students during the Fall 2018 semester. For each OEMP, I describe the setup, the learning objectives (including the categories of engineering judgment addressed), the tasks that I asked students to do, and how these tasks accomplished the learning objectives.

Context

The Fall 2018 semester was the third contiguous semester that I had taught the sophomore-level aerospace mechanics of materials course at the University of Michigan. This semester there were 47 students enrolled. The course covers topics of statics, axially-loaded bars, finite element analysis for trusses, torsion, one-dimensional beam bending, and three-dimensional states of stress and strain. In the first two semesters I taught this course, all of the homework problems were closed-ended computational problems where students analyzed a given structure in pursuit of a correct answer. During the summer between my second and third semester teaching, I made the decision to re-frame the course to emphasize mathematical modeling. This included changes both small—such as emphasizing the word “modeling” throughout the course—and large—designing the two OEMPs to be included in the homework.

The context chosen for the both OEMPs was a hypothetical bridge spanning between the aerospace building and an adjacent laboratory building on campus. I chose a civil engineering scenario such as this for an aerospace course because all students have experience using bridges, and I thought that this experience would help them to better visualize the mathematical models they created and better connect these to the “real world.”

Students were given OEMP 1 as a part of homework 3 (assigned in the 3rd week of class) and OEMP 2 as a part of homework 9 (assigned in the 13th week of class). Each OEMP was worth half of the points on that homework assignment. Students were also allowed to drop their lowest homework grade of the course, and the two homework assignments that included OEMP were not exempt from this. So, students could skip one OEMP with no impact on their final grade.

Both of the OEMPs prioritized conceptual understanding and the problem-solving process over correct final answers. As a result, I graded students primarily on their justifications for their models and their mathematical problem-solving processes. I mentioned this emphasis on justification frequently in class and office hours, telling students that there were no "right or wrong answers," just "well-justified and poorly-justified answers."

Open-Ended Modeling Problem 1

The learning objectives of OEMP 1 were for students to engage in the following three aspects of engineering judgment:

2. Making assumptions or simplifications to be the bases of mathematical models
7. Discretizing (grouping elements to reduce the number of types to be designed)
8. Determining what elements or conditions were "typical" (representative) for the structure)

Two additional learning objectives were for student to:

- Gain more practice solving closed-ended statics problems
- Understand how the provided model and design criteria were both simplifications from the real world

At the time OEMP 1 was assigned, the course had only covered statics and definitions of normal and shear stress and strain. Because of this, I provided students with a simplified, statically determinate model of the bridge (Figure 1). In class discussions, I told students that the model of the bridge was highly simplified and not realistic, but we had to make these simplifications in order for them to be able to solve the problem.

I also gave students a non-exhaustive list of ways in which the bridge would be used, which included people by themselves (e.g. students, faculty, and tour groups) and people transporting equipment (e.g. student project teams and aerospace technicians). This list was intended to suggest certain loads that students should consider; however, it did not include all loads that students eventually considered, such as the weight of the bridge deck itself. The description also stated that the bridge would be used year-round to encourage students to think about the effect of different seasons, such as considering the weight of snow.

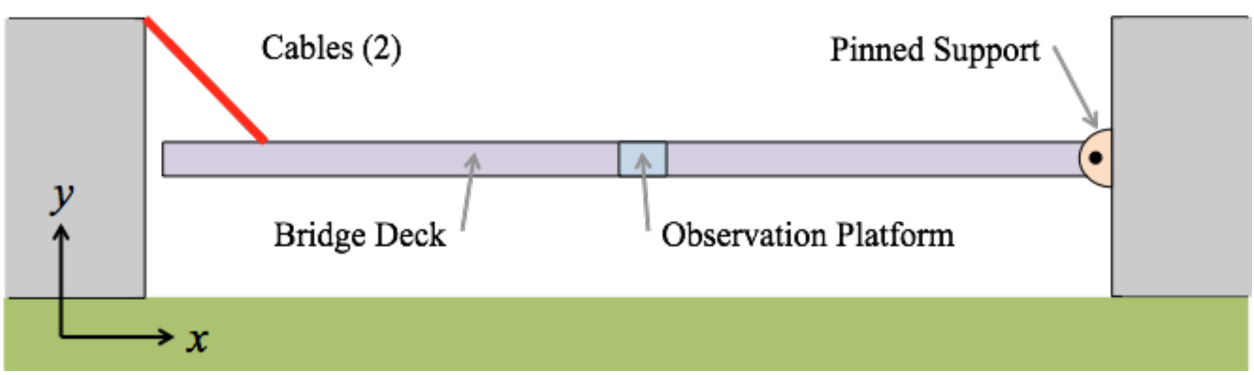

Figure 1. Model of the bridge given in open-ended modeling problem 1

Students were asked to complete five parts to the problem:

1. Estimate the external point and distributed loads acting on the bridge throughout the year. Justify all assumptions.
2. Draw a free-body diagram of the bridge and calculate the tension in one of the cables.
3. Using a provided table of material properties, select a material and diameter for the cables that is sufficient. Justify all answers. Determine if the size of the cable found is physically reasonable.
4. Discuss what a more accurate statically indeterminate model of the bridge might look like. Qualitatively assess how this might change the design of the cable.
5. Name two other factors beyond just strength that an engineer might consider when selecting the material and diameter for the cables holding up the bridge.

I expected students to engage their engineering judgment primarily during part 1 of OEMP 1. Students first had to determine *what* representative loads they would add to their model of the bridge (engineering judgment category #8), after which they had to determine *how* to model these loads in terms of their values (engineering judgment category #2) and the number of loads (engineering judgment category #7). For example, if a student decided to model the people on the bridge, they had to estimate the weight of a representative person and the number of people on the bridge at one time. Then, they needed to decide whether to model the people as a series of point loads or as one distributed load.

After students modeled the loads on the bridge, they calculated the tension in the cables (part 2) and the diameter of the cables required to support this tension given a material of their choosing (part 3). Students were not explicitly told to include a safety factor in these calculations, but they had learned about safety factors and I wanted them to take one into account. The calculations in parts 2 and 3 were more similar to the closed-ended, computational problems given in the other homework assignments, and they gave students more practice with solving statics problems. Lastly, students evaluated how true-to-life their model of the bridge and loads was by discussing whether their cable diameter was physically realistic (part 3), how they could change the model of the bridge to make it a "more accurate" statically indeterminate model (part 4), and two other factors beyond just strength that an engineer might consider when selecting the material and diameter for the cables holding up the bridge (part 5).

Open-Ended Modeling Problem 2

The learning objectives of OEMP 2 were for students to engage in the following two aspects of engineering judgment:

2. Making assumptions or simplifications to be the bases of mathematical models
4. Determining appropriate uses of technology tools

Other learning objectives were for students to:

- Have practice solving problems with statically-indeterminate beams

- Investigate ways to optimize a system with multiple parameters
- Understand how the provided model was a simplification from the real world

At the time OEMP 2 was assigned, the semester was nearly completed. Students had recently learned one-dimensional beam bending, which was used in OEMP 2. I provided students with a new statically indeterminate model of the hypothetical bridge between the aerospace building and the laboratory building (Figure 2). I told students to assume that the bridge deck was supported by four identical beams, and as a result they focused their analysis on one single beam. Unlike OEMP 1, in which students developed their own model of the loads on the bridge, I gave students a distributed load to use in OEMP 2. This load had a numerical first term that I determined from my calculations of the weight of people on the bridge and the weight of the bridge deck. This distributed load then had a variable second term that modeled the weight of the beam itself, which was a function of two parameters chosen by students: the density of the beam and the cross-sectional area of the beam.

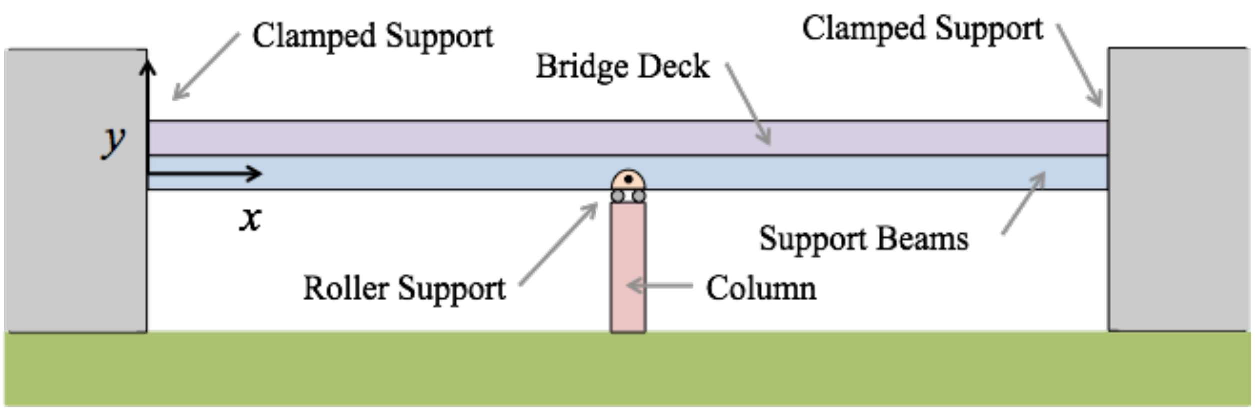

Figure 2. Model of the bridge given in open-ended modeling problem 2

Students were asked to complete five parts to the problem:

1. Write a symbolic equation for the bending moment throughout the beam as a function of the given distributed load.
2. Pick a material for the beam and a cross-sectional geometry for the beam that fits within an area 2 ft. wide by 2 ft. tall and gives a safety factor ≥ 2 everywhere in the beam.
3. Calculate the maximum deflection of the beam with the chosen material and cross-section and indicate where this occurs.
4. Calculate the total cost of the entire length of the beam with the chosen material and cross-section.
5. Describe a change to this model of the bridge that would make it more accurate (and therefore more complex), but still be solvable given the course content.

Part 1 of OEMP 2 was a traditional closed-ended problem with one correct final answer. It was students' first opportunity to solve a problem with a statically indeterminate beam, and many students found this part of the problem challenging and time-consuming. In fact, at least one student got so stuck on part 1 that they abandoned the assignment altogether. After solving for the bending moment equation, part 2 of the problem gave students an opportunity to engage their engineering judgment. I required students to calculate the maximum stress (and therefore the safety factor) for at least four different beams using two materials and two cross-sectional shapes. However, I also wrote in the assignment, "You are welcome (encouraged!) to write a computer program to help you efficiently test different materials and geometries." Furthermore, I encouraged students to use a computer program in their optimization of the beam by awarding bonus points to students with the lowest-cost beams that satisfied the safety factor and geometry constraints.

While students were not required to use software tools to optimize their beam, I hoped that these bonus points would encourage them to do so. Because I did not give directions on how to write such code, students were required to decide themselves how software would be most helpful (engineering judgment category #4). Furthermore, in writing their code, students had to make explicit and implicit assumptions (engineering judgment category #2). For example, I did not put a limit on the minimum web or flange thickness for an I- or T-beam. As a result, some students found that the best beam was an I-beam with a web thickness of 0, which is physically impossible. These students then had to decide whether it was ok to submit a final beam that was mathematically possible yet physically impossible.

After selecting a beam material and geometry, students completed parts 3 and 4, which were more similar to closed-ended computational problems. Lastly, similar to in OEMP 1, in part 5 students evaluated how true-to-life their model was by discussing how they could change the model of the bridge that I provided to make it a "more accurate" model, such as by adding additional columns to support the distributed load.

Student Response to Open-Ended Modeling Problems

While parts of these open-ended modeling problems (OEMPs) gave students practice with solving closed-ended computational problems, they were purposefully designed to give students an opportunity to engage in productive beginnings of engineering judgment. As a result, students were graded primarily on the justifications they gave for their models and the assumptions they made in constructing these. Similarly, we are unable to quantitatively assess how students achieved the learning objectives, or how the OEMPs helped students learn the technical content of the course (such as by comparing exam scores between this semester and a semester without the OEMPs).

We are, however, able to qualitatively assess students' response to the OEMPs. This is an important aspect of the evaluation of the OEMPs, because research has shown that fear of student resistance is a barrier to implementing new student-centered pedagogies [12], [13]. We obtained feedback on the OEMPs using a mixed-methods approach. Students were asked to participate in the research in two ways: a five-minute anonymous in-class survey and a one-hour reflective interview with the second author of this paper, conducted during finals week. Students were given the option to participate in none, one, or both of these data collection activities. Thirty-six students participated in the survey and five participated in an interview.

Student Survey

The survey asked ten Likert-style questions about how student felt about the OEMPs (possible responses: strongly disagree, disagree, neutral, agree, strongly agree), along with an open-ended response. All questions were optional. In this section we present data from four selected questions; full results can be found in the Appendix. We first analyze a series of questions that evaluated students' affective response to the OEMPs. Overall, students enjoyed completing the OEMPs with 27 of the 36 respondents (75%) saying they agreed or strongly agreed with the statement "I enjoyed completing the open-ended problems" (Figure 3).

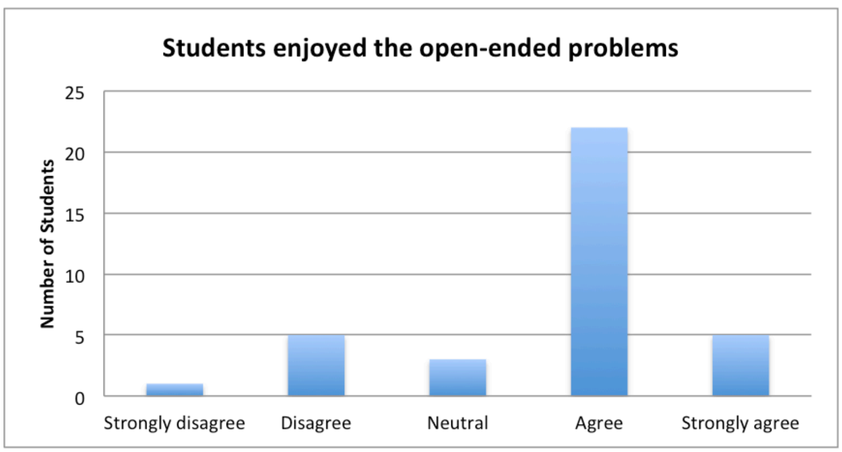

Figure 3. Students enjoyed the open-ended problems

To assess the degree to which students enjoyed the OEMPs, we asked "I like the open-ended problems more than the typical [course] homework problems." 20 respondents strongly agreed or agreed with that statement (55.5%), 8 strongly disagreed or disagreed (22.2%), and 8 remained neutral (Figure 4). This mix of responses is reflected in the open-ended comments, where students said they enjoyed the problems but experienced some frustration because they were unsure about the correctness of their answers or they spent a long time completing the problems, particularly OEMP 2 (due to the difficulty of calculating the bending moment in part 1).

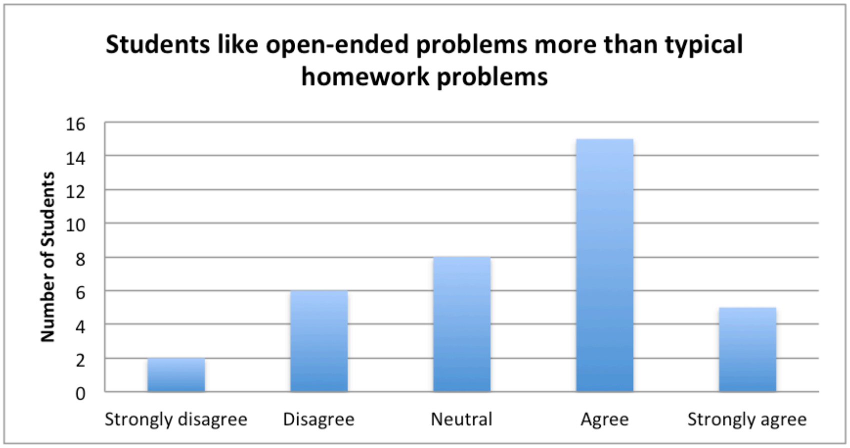

Figure 4. Students comparing OEMPs to typical homework problems

Students also responded to the statement "I'd like to have more open-ended problems like these in my other non-lab/non-design engineering courses" positively, with 28 or the 36 students (77.8%) responding strongly agree or agree (Figure 5). We take this as a promising sign that students want more OEMPs and we should continue to develop these kinds of problem for the first author's course and other aerospace engineering courses.

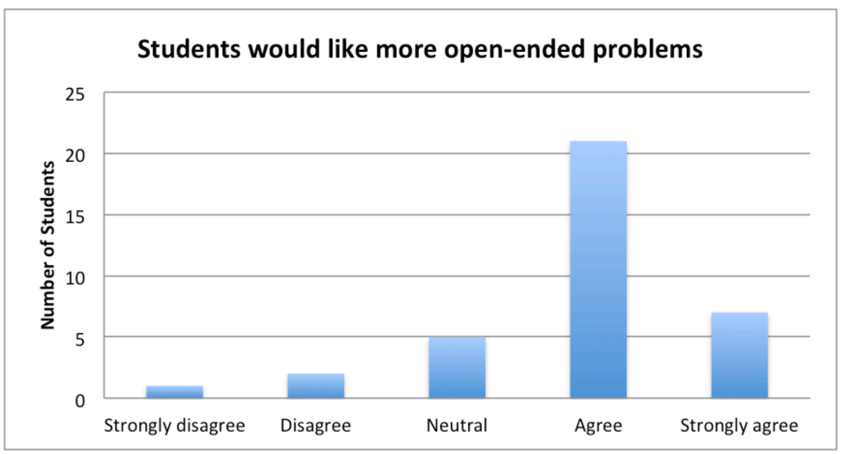

Figure 5. Students would like to have more OEMPs in their courses

Beyond evaluating how students felt about the problems, we also wanted to understand students' perception of how these problems fit with the rest of the course material. An overwhelming 35 of 36 students (97.2%) reported using mathematical models taught in the course when they completed the open-ended problems (Figure 6). This shows that we successfully designed the OEMPs in a way that directly addressed and reinforced the "conventional" mathematical models taught as a part of the course.

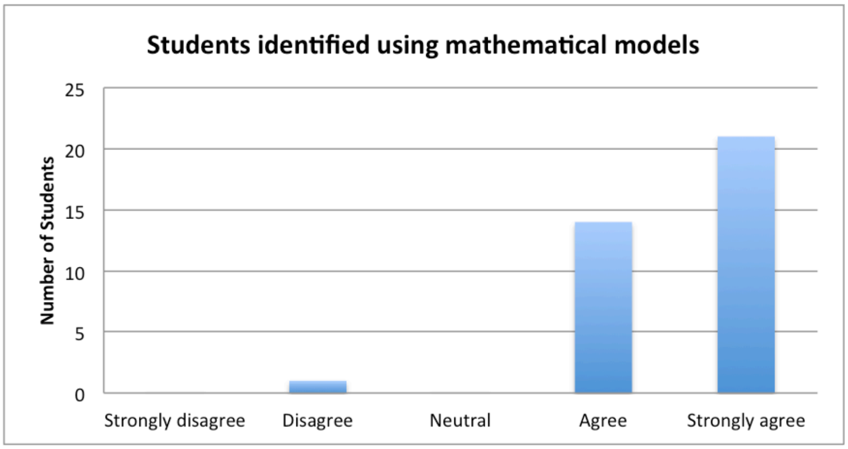

Figure 6. Students identified they used mathematical models

Student Interviews

Seventeen students consented to participate in research interterviews, which included sixteen male students and one female student. The one female volunteer was purposfully contacted to schedule an interview; however, she did not reply. Male students were randomly selected from the list of consenting students and e-mailed until five students agreed to meet for an interview. All five participants (pseudonyms Broderick, Hank, Henry, Oliver, and Sean) were high-performing male students in their sophomore year of the aerospace engineering program. The interviews began by asking students to describe how they solved each of the problems, followed by a series of questions asking students to evaluate their models. At the end of the interview, students asked what they thought of the OEMPs and some general demographic information. Interviews were audio recorded and transcribed by the second author for analysis.

In our companion paper we analyze these five students' thought processes as they completed the OEMPs [11]. Here, we examine only what they thought about the problems, and find four themes: 1) The OEMPs related to the real world, 2) the OEMPs helped to teach course concepts, 3) the OEMPs were fun, and 4) the OEMPs made the students think.

Two students discussed how they thought the OEMPs were a good addition to the course because they showed how the material applied to the real world and required them to practice skills they would need for their engineering careers. Broderick remarked twice that he "thought these problems were really good real world applications." Henry described how the OEMPs provided more real world practice than a standard problem:

> *You start out at a general [mechanics of materials] problem and then you kind of build on that to applying stuff not necessary from the class but that's kind of important in engineering, like picking from a long list of materials. That's something you're going to have to do later on. So I think it's more general engineering stuff.*

Henry also characterized OEMP 2 as an optimization problem and remarked that "Optimization, too, is kind of a big part of engineering." Without specifically naming engineering judgment in their interviews, students recognized our goal of designing the OEMPs to engage their engineering judgment, thereby making the course material more applicable to the real world and to engage students in aspects of the practice of engineering.

The second theme we found in the interview data was that students thought the OEMPs helped them better learn the course concepts. Hank reported, "I feel like [OEMP 1] helped me understand more of the concepts in the class." Sean, similarly, reflected, "But [OEMP 2] did force you to think about the concepts in the class and how these questions would relate to some sort of physical example." While we were unable to quantitatively assess how much the OEMPs helped students to learn the course concepts, we are encouraged that Hank and Sean felt that this was a benefit of the problems.

The last two themes across the interviews were both surprising to us. While we designed the OEMPs to be engaging, we were very encouraged that all five students interviewed described the OEMP as *fun*. This is particularly exciting given that the second author did not use the word "fun" in her interview questions. Sean said, "They were fun. I felt I was having fun while doing them." Henry similarly described his experience working on OEMP 2, "When I was sitting down doing this one on MATLAB, I kind of said to myself this one was actually kind of fun. It didn't really feel like just grinding some problems." Two other students reflected on how these problems were more fun than other kinds of homework. Broderick remarked" I think these were more interesting than plug-and-chug homework problems… kind of more fun." Similarly, Oliver remarked "This is a good problem. Plug and chug is… it's boring."

Lastly, two participants independently said they believed these problems made them think when doing their homework. Broderick, explaining why he would increase the number of OEMPs during the course from two to three or four, said "I think these are nice to make people actually think and use critical thinking skills and collaboration." Similarly, Hank explained why he thought it was good that students did these problems by saying, "This requires thought. You know what I mean? It requires thought, explanation, you know, like I had to logically kind of deduce where I thought the maximum bending moment would be." In their interviews, both of these students also contrasted the OEMPs to typical closed-ended computational homework assignments. While we are slightly concerned about the implication that these students describe their experience solving typical homework problems as not involving "thinking," we are encouraged that these students believe the OEMPs challenged them cognitively.

We were also pleased that these five students believed open-ended problems should remain part of the course, and some students even thought we should increase the number per semester or add additional open-ended, design problems. These interviews supported and further explained the survey data, and supports our continued integration of these problems into this course.

Limitations of the Student Interviews.
One prominent limitation of these interview data is that all five students were high-performing male students. This is due to the fact that, per the Institutional Review Board's approval for this study, students volunteered for interviews and the second author randomly selected students to interview from the volunteers. We did attempt to diversify the interview subjects based on gender by recruiting the one female student who volunteered, but were unable to do so. The lack of female volunteers is likely do to the gender makeup of the course, in which only 5 of 47 students (10.6%) were female.

Furthermore, because students were asked to volunteer for interviews after finishing OEMP 2, It is not surprising that the students who volunteered were the ones who enjoyed and saw value in the OEMPs. This was not the case for all students, as the survey results show. Six of 36 students (16.7%) who took the survey disagreed or strongly disagreed with the statement "I enjoyed completing the open-ended problems" (Figure 3). And, 8 of 36 students (22.2%) said that they liked the typical homework problems more than the OEMPs. As is discussed earlier, students' open-ended comments on the survey suggest that possible explanations for these negative opinions could be the length of the problems and being unsure of the correctness of their answers. While there will likely always be students who do not like open-ended problems, it is important to understand if there are ways in which we can improve on the OEMPs, either in the problem itself, the administration of the problem, or the way the problems are introduced and framed by the instructor. Based on students' feedback, we have already made changes to the OEMPs assigned during the Winter 2019 semester, as is described in the next section.

Conclusions and Future Work

In this paper we have described a sequence of two open-ended modeling problems (OEMPs) designed to engage students in the first author's sophomore-level aerospace mechanics of materials course in productive beginnings of engineering judgment about mathematical models [10]. These OEMPs give students an opportunity to make assumptions when developing mathematical models, discretize elements, determine representative elements for a model, and determine the appropriate use of computer code in solving an optimization problem. Students are no longer just completing closed-ended computational homework assignments; instead they are applying the course content to model and analyze a real-world system with some necessary simplifications. In addition to presenting our OEMPs, we have investigated student opinions of these OEMPs through analysis of a student survey and student interviews that show students liked the problems because they related to the real world, helped to teach course concepts, were fun, and made them think.

We have continued this work during the Winter 2019 (W19) semester, implementing revised OEMPs in the first author's aerospace mechanics of materials course. While the general idea of the problems remained similar, there were two substantial changes. First, we changed the context of the problem from analyzing a bridge to analyzing the *Nomad*, an airplane in the atrium of our aerospace building [14]. And second, to encourage self-assessment of their models, we gave students an entire class meeting to discuss their models in a small group of four.

In W19 OEMP 1, students were given a model of the airplane's landing gear that considered the main landing gear as two-force members. Students were asked to model the airplane as a set of forces and moments, calculate the internal force on the main landing gear, and then select a suitable material and diameter for the main landing gear. In doing this modeling, we instructed students to size the landing gear for actual operations, which required them to model the forces and moments on the airplane in the operational scenario that would put the greatest load on the landing gear. Many students also considered scenarios where the plane was accelerating, requiring them to develop fictitious forces modeling this accelerating.

In W19 OEMP 2, students were asked to optimize the airplane's spar in a manner similar to Fall 2018 (F18) OEMP 2. One change was that students completed the closed-ended calculations of the spar's bending moment on the previous homework assignment. This was in response to students' feedback about spending a great deal of time calculating the bending moment in F18 OEMP 2. Students were then given the solutions to this assignment, which ensured that all students use the correct bending moment equation in their optimization of the beam. We hoped that this would give students more time to focus on the optimization.

Each OEMP was due at the beginning of a class meeting, and students spent the duration of that class discussing their models in a small group of four. We added this activity because self-assessment is an important component of teaching mathematical modeling to students [9] and students in Fall 2018 had no opportunity to evaluate their model or iterate upon it. For W19 OEMP 1, students in each group compared their models and then worked together to combine the best parts of their individual models into the best group model that they could make. For W19 OEMP 2, students in each group compared their final beam designs and their optimization process, and then worked together to create a group optimization code that determined the lowest-cost beam.

We are also collecting more data to better investigate how students approach and solve these OEMPs. Similar to the Fall 2018 data, we interviewed six students (including one female student and, based on the conversation with the second author, not all high-performing students) and conducted a survey with all students. We also collected students' submitted work for the OEMPs, which gives us information about how a wider range of students of different genders and final course grades approached the problem. Finally, we took audio recordings of select student groups as they discussed their OEMPs in class, which will allow us to investigate how students evaluated their models in this setting. We anticipate in-depth investigations, assessments, and evaluations of students' productive beginnings of engineering judgment such as these to be increasingly important given that the new 2019-2020 ABET Student Outcomes include the explicit connection of engineering science content and design (outcome #1) and the explicit inclusion of engineering judgment in outcome #6 [15].

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Appendix: Full Student Survey Results

Statement	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I knew what the expectations were from me when completing the open-ended problems.	0	2	2	23	9
I was confident that my models of the bridge were good models, given the amount of structures knowledge I had at the time.	1	3	12	18	2
I was confident in the answers that I submitted for the open-ended problems.	1	7	6	16	6
I used the mathematical models taught in [this course] when completing the open-ended problems.	0	1	0	14	21
I looked up information from the internet or other references to use in completing the open-ended problems.	2	11	8	8	7
Before the semester started, I expected to do open-ended problems like these in [this course].	6	17	7	6	0
I have done open-ended problems like these in my other non-lab/non-design engineering courses.	8	17	5	4	2
I'd like to have more open-ended problems like these in my other non-lab/non-design engineering courses.	1	2	5	21	7
I enjoyed completing the open-ended problems.	1	5	3	22	5
I like the open-ended problems more than the typical [course] homework problems.	2	6	8	15	5