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Abstract
This paper presents a study of students solving open-ended modeling problems (OEMPs) in a sophomore level aerospace mechanics of materials course. OEMPs are homework problems that have no correct answer and ask students to create a model to solve a problem in a real world context. Students were asked to solve two of these problems as part of their regular homework assignment. Through interviews, five students in the course described their problem solving process and evaluated their models. Our analysis found students exhibited the productive beginnings of engineering judgement when creating their models. We also found students enjoyed and wanted more OEMPs given in their classes. Implications include creating more OEMPs for different types of engineering science courses and implementing a discussion or reflection for students after they turn in the problems.

Introduction
Creating and analyzing models of physical systems is a core activity of engineering. In modern times, much of this work is done with computer software, yet the backbone of these analysis programs are mathematical models. Students learn how to use and manipulate these models in the core technical courses of their discipline, which we call engineering science courses. In introductory engineering science courses--such as fluid mechanics, thermodynamics, statics, and mechanics of materials--students learn simple models that require many assumptions to use. As students advance in their studies and specialize, the models become more complex as fewer assumptions are made.

Engineering science courses are typically taught with a lecture-based pedagogy and assign students sets of homework problems to engage them in practicing the course material outside of class time. Problem sets usually comprise problems from the course textbook or are written by the professor. Although the number and length of problem sets varies by instructor, a problem set typically takes several hours of work (and in the U.S., a 3-credit-hour 12-week undergraduate course assumes 6 hours per week of out-of-class work). In an undergraduate curriculum, students are typically required to take at least 10 engineering science courses. Therefore, we can estimate a typical engineering student spends 720 hours working on these type of problem sets during their undergraduate career. Yet, there is little research about how students are learning while working on these problem sets. The first author of this paper has addressed this in her prior work, and this study of open-ended modeling problems is derived from her findings [1]. Examining students working on homework in control systems and fluid mechanics courses, she found students are mostly engaged in conversations to get their homework done instead of conversations to build knowledge about disciplinary concepts. We as a research team are interested in designing and analyzing homework problem that engage students not only in
mathematical problem solving, but in developing other skills and knowledge students need for their future careers in engineering.

A typical homework problem is a well-defined mathematics problem that asks the student to apply a formula or problem-solving process that was recently covered in class to arrive at a single, correct numerical answer. While these types of problems are important for understanding and practicing mathematical problem-solving processes, these well-defined problems are not the type of problems engineers will be expected to solve in the workplace [2],[3]. Ethnographic studies of engineers in the workplace [4]-[6] show that professional engineers deal with ill-defined, complex problems that take into account myriad criteria and constraints, including (but not limited to) financial, environmental, and technical.

Our research team’s goal is, through qualitative research of student problem solving, to design open-ended (no unique correct solution or answer) engineering problems that develop skills students will need in the workplace, and that put more focus on conceptual understanding and the problem-solving process and less focus on getting a single correct numerical answer. In this study, we target the skill of engineering judgment, specifically with with respect to creating mathematical models of real-world scenarios. Research has shown that while modeling is commonly implicitly taught across the engineering curricula [7],[8], students learn these practices best through the explicit inclusion of modeling in the curriculum [9].

One evidence-based approach for incorporating real-world mathematical modeling into undergraduate engineering education is through Model-Eliciting Activities (MEAs) [10]. These activities are intended to replace the traditional approach to teaching mathematical modeling, in which “conventional mathematical models and well-formulated procedures are disseminated by the instructor and are intended to be acquired by the students” (p. 5). This instructor-centered pedagogy has been found to be less effective for promoting student learning [11]. MEAs are student-centered, and they give students the opportunity to develop the mathematical models themselves. In doing so, 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” (p. 20). Model-Eliciting Activities are the first step to a three-stage model development sequence. Second are Model-Exploration Activities, in which students evaluate their models and compare/contrast them with existing “conventional” engineering models. Third are Model-Adaptation Activities, in which students apply or adapt their models, such as by writing code that implements them. Research on MEAs have investigated topics such as how students make and use representations during MEAs [12],[13], ways to evaluate students’ work for evidence of conceptual understanding [14], feedback provided to students in the context of an MEA [15]-[17], and the implementation of MEAs in the engineering curriculum [18],[19].
In this pilot study, our research team developed two open-ended modeling problems for a 200-level mechanics of materials course taught by the second author of this paper in an aerospace engineering department. These problems both involved modeling and analyzing a hypothetical bridge on campus. This paper examines interviews with five students from the course and asks:

RQ2. How do students evaluate their mathematical model and final answer?

In order to answer this question, however, we first need to investigate the process that these five students used when solving the open-ended modeling problems. Therefore, in our paper we first ask the question:

RQ1. How do students chart a solution path and solve an open-ended modeling problem?

While this paper focuses on these two research questions, details about the design of the open-ended modeling problems and an analysis of student feedback can be found in our companion paper [20].

Theoretical Framework

Engineering Judgement

Our theoretical framework is derived from Gainsburg’s work studying structural engineers [6]. In her 2007 study, she followed structural engineers at two firms as they completed different tasks and observed their use of mathematics. During her observations, she encountered the phenomenon of engineering judgement, or using “judgement to make a final call on the reasonableness of the analysis or design” (p. 287).

While Gainsburg’s definition of engineering judgment is specific to the use of mathematical models by practicing structural engineers, there are still many aspects of her definition that provide a useful framework for the use of mathematical models by aerospace engineering students. Analyzing all incidents of engineering judgement in the data, Gainsburg concluded they fall into the following categories:

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 [6, pp. 486-487]
It is clear that undergraduate aerospace engineering students are not expected to possess well-developed engineering judgment. Furthermore, they would not be expected to even begin to develop engineering judgment in some of these categories, such as #6, *overriding official building codes*. However, we see five of these categories as applicable to the open-ended modeling problems in our study. The four underlined categories in the list above address the first research question *(How do students chart a solution path and solve an open-ended modeling problem?)*, and the one bolded category addresses our second research question *(How do students evaluate their mathematical model and final answer?)*. As such, this study probes not just how students engage with open-ended modeling problems, but more generally how they exhibit the productive beginnings of engineering judgment.

**Framing**

In analyzing students’ evaluation of their answers to the open-ended modeling problems (Gainsburg’s first category of engineering judgment), we saw that another influence on how they judged the “goodness” of their mathematical models was their *framing*. Framing is the set of expectations one has about a situation [21, 22]. In our study, some students framed their solution as meeting the expectations of the instructor, while in other instances students discussed their solution as if they were analyzing a bridge that would be built in the real world. Similarly, Koretsky and Nolen found students discussing their projects either in the “school world” or the “engineering world” when examining chemical engineering middle year studio and senior design teams [23, 24], and McNeill et al. found similar results where students distinguished between “classroom problems” and workplace problems” [25]. Gainsburg also found different ways that students framed mathematics in engineering courses: from believing that every engineering problem has one correct solution (a novice viewpoint) to understanding that mathematics are subjective, contextual, and fallible (an expert viewpoint, and one which students in her study did not demonstrate) [26].

**Methods**

**Course Context**

The course we studied is a 200-level mechanics of materials course in an aerospace engineering department at a large public university in the Midwestern United States. The course comprises mostly sophomore students and is one of the first courses students typically take in the aerospace department. Fall 2018, the semester we studied, was the third consecutive semester the second author taught this course, and the first semester in which he used open-ended modeling problems. 47 students were enrolled in the course at the end of the semester.

Two open-ended modeling problems were given to all students to solve as part of homework assignment 3 (assigned in the 3rd week of class) and homework assignment 9 (assigned in the 13th week of class). Each open-ended modeling problem was worth half of the points on that
homework assignment. Both open-ended modeling problems were themed around a hypothetical bridge between the aerospace building and another building on campus. This civil engineering scenario was chosen under the assumption that all students have personal experience using bridges, and that this experience would help them to better visualize their mathematical models and connect them to the “real world.”

Open-ended modeling problem one (OEMP1) on homework 3 asked students to estimate the external point and distributed forces acting on the hypothetical bridge (Figure 1). The second author provided students with a base model of the bridge (but not the forces) to ensure that the problem would be solvable with three weeks of content knowledge. In the problem description, students were told the bridge would most likely be used by students, faculty, tour groups, and technicians for moving equipment between buildings. When announcing this problem in class, the second author hinted that students should also consider the varying climate’s effect on the bridge. Once students modeled the forces on the bridge, they had to solve the equilibrium equations to calculate the stress on two metal support cables, and then they selected a material for these cables and calculated their required diameter to support the forces they had modeled.

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

In the beginning of the open-ended modeling problem description, the second author gave students information about the purpose of this problem, saying:

*As I’ve said before, one of the objectives of this course is to show you ways in which we can use various mathematical models to represent and analyze (simplified approximations of) real-world systems. There’s no better way to learn this than to practice. So, on different homework assignments this semester, I’m going to give you an open-ended modeling problem. There is no single “right answer” to this problem. If you put thought into your modeling and justify your numbers and assumptions, you will do well on these problems.*

Open-ended modeling problem two (OEMP2) on homework 9 asked students to consider a more complex model of the same bridge (Figure 2). In this problem, students were given the external
distributed force on the bridge, as determined by the second author, and were asked to first calculate an equation for the bending moment over the length of the bridge. This part of the problem was closed-ended, in that there was one correct answer. After calculating this bending moment, students were then asked to determine the cross-sectional geometry (within given limits) and material of one of the main support beams that ran the length of the bridge, such that it had a safety factor of at least 2 (meaning that the beam would fail at stresses twice those experienced with the loading condition given by the second author). Students were asked to show calculations for at least four beam designs using at least two different geometries and two different materials. Performing each of these sets of calculations required an iterative process, as the material and geometry that a student selected influenced the weight of the beam, which was a factor in the beam’s bending moment and therefore the stress that it experienced. Lastly, students were asked to choose one material-geometry combination and calculate the maximum deflection and cost of this beam.

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

This was end of the required questions, but the second author also noted that the setup of the problem led to an interesting optimization question: “What is the lowest-cost beam that fits inside the cross-section limits and gives us a safety factor of at least 2?” The second author challenged students to find the lowest-cost beam that satisfied these requirements, and stated that he would give extra credit to the students with the five lowest-cost beams. While many students attempted this optimization in an effort to find the lowest-cost beam, this was not required to receive full credit on the homework.

Because these open-ended modeling problems prioritize conceptual understanding and the problem-solving process over the final answers, students were graded primarily based on the justifications they gave for their models and the mathematical problem-solving process they employed. For OEMP1, students needed to include the weight of the bridge itself or people on the bridge as one of the forces loading the bridge, but there were no other “required” forces. Students just had to show reasonable justifications for their assumptions. Furthermore, when asked to calculate the stress on the support cables and choose a diameter for these, students were
graded based on the process they followed, and not whether their answer was correct given their model of the bridge. Grading for OEMP2 was similar, in that students were assessed on their problem-solving process rather than achieving correct final answers.

Data Collection
To recruit participants for the study, the first author made an announcement during class and passed out consent forms. She returned the next class period to collect the forms. Students were asked both to participate in an interview and to have their homework scans reviewed by the research team. Seventeen students consented to be interviewed for the study, and only one was a woman. The one female volunteer was purposefully contacted to schedule an interview; however, she did not reply. For the remaining sixteen students, the first author used a random number generator to select the first six participants to be e-mailed, and continued using this pattern until five students agreed to meet for an interview. The five participants (pseudonyms Broderick, Hank, Henry, Oliver, and Sean) were all male aerospace engineers in their sophomore year. One of the five students transferred in at the beginning of the semester from another university. All participants were high-performing students in the class. All received no more than 2 points off out of 50 on either of the studied homework assignments, and many received full credit.

The interview protocol (Appendix I) began by asking students how they solved each of the open-ended modeling problems, followed by a number of questions about their model’s completeness, accuracy, and approximation to reality. The second portion of the protocol asked their opinion of the open-ended modeling problems and asked them to compare these problems and this class to other engineering classes they had taken.

Interviews were audio recorded and transcribed by the first author. Transcripts were annotated, highlighting interesting responses. The first and third author examined four themes between the five transcripts: 1) students’ solution path for open-ended modeling problem one (OEMP1), 2) their solution path for open-ended modeling problem two (OEMP2), 3) their claims and justification of the completeness and accuracy of their models in both OEMPs, and 4) their thoughts about the problem types overall.

Analysis of Student Data
First, we present the solution paths that students took when loading their bridge in OEMP1 and choosing their beam material and geometry in OEMP2. This addresses our first research question (How do students chart a solution path and solve an open-ended modeling problem?), and provides context for our second, and more important analysis which addresses our second research question (How do students evaluate their mathematical model and final answer?)

Approach to Open-ended Modeling Problem One
Students were told they could load the bridge with whatever forces they wanted to as long as they gave good justifications for their choices. Most of the students focused on the different types of people who would be using the bridge and equipment that would be moved over the bridge, both of which were forces mentioned in the OEMP1 assignment given to students. Some students also considered weather conditions or the weight of the bridge, which were not explicitly mentioned in the assignment. For each of their chosen forces (engineering judgment category #8, determining what elements or conditions were “typical” (representative) for the structure), we present the our analysis of the assumptions the student made (engineering judgment category #2, making assumptions or simplifications to be the bases of mathematical models) and their discretization, or how they applied that assumption as a force to their model (engineering judgment category #7, discretizing).

Table I: Approach to Open-ended Modeling Problem One

<table>
<thead>
<tr>
<th>Representative Elements of Load</th>
<th>Oliver</th>
<th>Sean</th>
<th>Henry</th>
<th>Hank</th>
<th>Broderick</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Assumptions</td>
<td>A person needs 5 square feet of space based on dance club capacity.</td>
<td>A person weighs 170 lbs. 60 tourists, 40 students, and 20 other people on the bridge at one time.</td>
<td>A person weighs 500 lbs. People are on the observation deck.</td>
<td>An average person weighs 150 lbs. No more than 1000 people on the bridge.</td>
<td>An average person weighs 170 lbs. Analyzing winter, so people huddle together for warmth.</td>
</tr>
<tr>
<td>Discretization</td>
<td>Distributed force of the total number of aerospace department faculty and graduate students.</td>
<td>Point forces of people to make a &quot;worst case scenario.&quot;</td>
<td>Distributed force of people on the observation deck.</td>
<td>Distributed force with constant magnitude.</td>
<td>One point force representing 5 people.</td>
</tr>
<tr>
<td>Equipment</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Assumptions</td>
<td>Student groups moving equipment.</td>
<td>Equipment would be rolled across the whole bridge.</td>
<td></td>
<td>A machine weighs 300 lbs, and is pushed by one person.</td>
<td></td>
</tr>
<tr>
<td>Discretization</td>
<td>Two point forces representing two pallet trucks.</td>
<td>Distributed force.</td>
<td></td>
<td>One point force representing a single machine.</td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Assumptions</td>
<td></td>
<td></td>
<td>Winter. Snow weighs 7 lbs per square foot. Average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Many of the assumptions our five participants made were expected, such as finding or guessing the average weight of a person. A few went further in their research, such as finding the square footage required per person in a dance club or looking up the average snowfall in the University’s location and the weight of snow to load the bridge.

**Approach to Open-ended Modeling Problem Two**

OEMP2 asked students to choose the material and geometry of a beam, and to find the lowest-cost beam that had a safety factor of two. Students varied in how they made these choices, with some students making decisions based off gut feelings and others writing an optimization code and letting it run many different models to find the best one. For each student we present our analysis of their use of code (engineering judgment category #4, *determining appropriate uses of technology tools*) and the assumptions they made (engineering judgment category #2, *making assumptions or simplifications to be the bases of mathematical models*).
Picking Beam Geometry

<table>
<thead>
<tr>
<th>Factor of two.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student chose I-beam.</td>
</tr>
<tr>
<td>Student picked I-beam and T-beam, then manually tweaked geometry by hand.</td>
</tr>
<tr>
<td>Code determined I-beam was better than T-beam. Then student ran models for lowest cost for safety factor over two.</td>
</tr>
<tr>
<td>Student picked shapes to get safety factor. Chose easy numbers and reduced values to get closer to safety factor of two.</td>
</tr>
<tr>
<td>Picked geometry so he didn't have to calculate the centroid.</td>
</tr>
</tbody>
</table>

Assumptions

<table>
<thead>
<tr>
<th>You could make a bridge out of concrete.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most beams in the world are I-beams so that must be best.</td>
</tr>
</tbody>
</table>

The five students had a spectrum of code usage from Oliver, who used code to determine the measurements of his I-beam (left, Table II) and his material, to Hank, who did the entire problem by hand (right, Table II). Two students (Sean and Henry) inputted the given chart of material properties into their code and used it to pick their beam material, but then chose the shape or tweaked the exact measurements of their beam by hand. In the interviews, students pointed to time being a limiting factor of why they didn’t fully optimize their beam using code to find the best solution.

**Evaluation of Open-ended Modeling Problems**

We present our interpretation of students’ evaluation of their open-ended models based on the frame in which they were evaluating their model—whether they were considering their model to be good or bad based on the conditions in the real world or the requirements of the course.

**Table III: Evaluation of Open-ended Modeling Problem One**

<table>
<thead>
<tr>
<th>Evaluation of Model</th>
<th>Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Course</td>
</tr>
<tr>
<td><strong>Good</strong></td>
<td>Broderick: The model used all of the course content that he had learned up to the point at which OEMP1 was given.</td>
</tr>
<tr>
<td></td>
<td>Oliver: His calculation of the cable diameter reflects his personal experience, in that he has seen actual cables with this diameter.</td>
</tr>
<tr>
<td><strong>Bad</strong></td>
<td>Hank &amp; Sean: Because of students' knowledge when they were given OEMP1, the model is too simplified to really represent the real world.</td>
</tr>
</tbody>
</table>
For OEMP1, most of the students evaluated their models as if their bridge would be built in the real world. Broderick and Oliver argued they developed “good” models based off of their personal experience, as they had seen people behave in a certain way during winter in the University’s location (Broderick), or they had seen metal cables with the diameter they calculated (Oliver). Hank, Sean, and Henry determined their models were “bad” because they understood their model was too simplified (because they had only learned three weeks of course content at the time of OEMP1), did not incorporate enough representative elements, or resulted in unrealistic numbers. Because the interviews were held at the end of the semester, many students commented that in hindsight they knew their model for OEMP1 was not a good model because they had learned more advanced mathematical models over the semester and could now produce what they considered to be a better model.

Table IV: Evaluation of Open-ended Modeling Problem Two

<table>
<thead>
<tr>
<th>Evaluation of Model</th>
<th>Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Course</td>
</tr>
<tr>
<td><strong>Good</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broderick: I refined my answer until I got what I think &quot;he&quot; [the instructor] wanted.</td>
</tr>
<tr>
<td></td>
<td>Broderick &amp; Sean: He felt he followed the &quot;correct&quot; closed-ended problem-solving process (He didn't make a mistake in his math).</td>
</tr>
<tr>
<td></td>
<td>Hank: The model helps him to understand the course content.</td>
</tr>
<tr>
<td></td>
<td>Henry: His solution satisfied all of the requirements set out in the problem statement.</td>
</tr>
<tr>
<td></td>
<td>Henry &amp; Oliver: He used MATLAB to test lots of different beams (Oliver: &quot;Because of the calculations.&quot;).</td>
</tr>
<tr>
<td><strong>Bad</strong></td>
<td>Broderick: He could have done more work to optimize the beam with a computer program.</td>
</tr>
</tbody>
</table>
In their evaluation of OEMP2, students thought their models and decisions were “good” in the frame of the class but “bad” in the frame of the real world. Many students also stated their model was good because they had met all the expectations of the assignment, done all of their math correctly, and followed the right procedures.

In comparing their models in both OEMPs, students claimed their model for OEMP2 was a better model in the real world because they had learned more sophisticated mathematical models in class that considered more aspects than their model for OEMP1. And, the assignment for OEMP2 inherently asked students to investigate the bridge in more detail by looking at the stress and deflection along the bridge’s entire length. This is contrasted to OEMP1, where students sized two support cables and ignored deformation of the bridge deck. Yet, many of them also noted that their model for OEMP2 still wasn’t “good” in the frame of the real world because they knew they would learn more mathematical models with fewer simplifying assumptions in the subsequent 300-level mechanics of materials course, and would therefore be able to model the bridge in more detail.

Other reasons students reported their models were “bad” were they had never seen a bridge made of granite or they thought the calculated deflection didn’t seem realistic. Oliver, the one student who used code to determine his beam dimensions, also reflected that he knew his beam was theoretically correct, but he had produced an I-beam with a flange thickness that was physically unreasonable in the real world.

**Discussion**
In this study we conducted five interviews with aerospace engineering students about solving and evaluating two open-ended modeling problems they completed for homework in their mechanics of materials course. After reviewing how they chose to model each of the two problems, we analyzed the different ways they evaluated their models. In these analyses of students’ practices, we are not claiming that they are exhibiting engineering judgment at the same level of a professional engineering, nor that they should be able to do so at the end of a
sophomore-level introductory mechanics of materials course. However, in synthesizing the ways
that students evaluated their models across the two open-ended modeling problems, we see three
overall ways in which students displayed productive beginnings of engineering judgement.

First, most students interviewed decided to use code to aid them in their optimization and
analysis during open-ended modeling problem two (OEMP2) (engineering judgment category
#4, determining appropriate uses of technology tools). Oliver, the student who relied on code the
most, was confident in his analysis being “theoretically” right because his code had determined
the best model. Other students, who used code to pick the material or as a calculator, reported
that they knew using more code to optimize the problem would have given them a better answer
but chose not to because of lack of time. Therefore, students recognized the advantages or
potential advantages of using code to assist in their modeling.

Second, when evaluating their models, students often reported that they had confidence in their
model because they had seen something in the real world with similar dimensions. Similarly,
students knew their model was flawed because they hadn’t seen anything made like that in real
life or it just “didn’t seem right.” For open-ended modeling problem one (OEMP1), students also
used their knowledge about weather and their environment--along with online research--to make
decisions about how they loaded the bridge. In these ways, students used their “lived
experiences” to identify representative elements for their model (engineering judgment category
#8, determining what elements or conditions were “typical” (representative) for the structure)
and to evaluate their model (engineering judgment category #1, determining what is a good or
precise enough calculation or estimation). This finding resonates with previous research that has
found that pre-college students rely on their own lived experiences to navigate an ill-defined
problem in ways that are productive beginnings of expert engineering design behavior [27], [28].

Lastly, students recognized when their models or knowledge was limited (engineering judgment
category #1). In the interview, we did not prompt students to evaluate their model in any
particular frame. We simply asked how they knew their model was accurate, complete, an
acceptable approximation to reality, and the best model. All five students independently
recognized that their models could be evaluated in the frame of the course or in the frame of the
real world. Students also understood that the sophistication of the bridge models as provided by
the instructor (the second author) and their ability to analyze these models deepened over the
course between OEMP1 and OEMP2, and it would continue to grow in the subsequent 300-level
mechanics of materials course. The students all recognized that their models all had inherent
assumptions or simplifications (engineering judgment category #2, making assumptions or
simplifications to be the bases of mathematical models) due to their level of knowledge, even if
they weren’t able to overcome these simplifications.
There are a number of limitations in this study, our first focused on open-ended modeling problems. The largest limitation is the lack of gender and class performance diversity in our interview participants. Our participant selection was limited by the fact that students self-selected to participate in the interviews per our Institutional Review Board (IRB) approved study methodology. We could not intentionally select participants to ensure diversity of subjects. As recruitment took place late in the semester, it is reasonable to consider lower performing students in the class would be hesitant to volunteer to participate. We were also limited by the gender makeup of the course, in which only 5 of 47 students (10.6%) were female. Knowing this might be an issue, our IRB methodology allowed us to recruit any female students who volunteered to participate instead of leaving it to chance through random selection. Unfortunately, our one female volunteer did not respond to recruitment emails.

Conclusions and Future Work

In this paper, we found evidence of students displaying the productive beginnings of engineering judgement. From Gainsburg’s work [6], we understand developing engineering judgement is essentially developing expertise. These students are at the beginning of their careers and need many more years of practice; yet, we saw evidence of these students demonstrating five of the eight engineering judgement practices Gainsburg outlines in her paper. Therefore, this study also gives us evidence that open-ended modeling problems (OEMPs) are a productive exercise to include in engineering science courses. Not only do they give students more practice with ill-defined, workplace type problems [2], but they also give students opportunities to develop modeling skills and experiences that build engineering judgement.

We recommend that researchers and instructors continue to develop OEMPs for other courses and disciplines beyond mechanics of materials in aerospace engineering, as we have studied in this paper. When developing these OEMPs, researchers and instructors should design the scenario and questions to address categories of engineering judgment relevant to their course and discipline. While Gainsburg [6]’s definition of engineering judgment comes from observing structural engineers, many categories are general enough to apply to any discipline. Furthermore, OEMPs can also include closed-ended parts that give students practice employing the “canonical” formulae taught in class. These closed-ended parts can occur at the beginning before students engage in the open-ended mathematical modeling (as in our OEMP2) or at the end (as in our OEMP1). Students also recognized that their knowledge and ability to create more detailed models increased throughout the semester, and would continue to increase when taking their next mechanics of materials course. Therefore, we recommend that researchers and instructors develop OEMPs that span multiple courses, giving students the opportunity to compare a larger number of models with different approximations and simplifications.
We also recommend the addition of these types of problems to engineering science courses because students enjoyed the process of solving them. In the interviews we conducted, all five students reported liking the experience of doing the OEMPs. Students reported that they thought these problems made them think more than typical “plug and chug” homework problems and helped them understand the material better. When asked if we should continue to include these problems in class, all students agreed we should continue to include them with half the students thinking more should be added. This opinion was also held by other students in the course who were not interviewed. In a survey at the end of the semester, 75% of students (27/36) agreed or strongly agreed that they enjoyed completing the OEMPs, and 78% of students (28/36) agreed or strongly agreed that they’d like to have more open-ended problems like these in their other non-lab/non-design engineering courses. For a more detailed analysis of students’ opinions of the OEMPs, please see our companion paper [20].

Furthermore, our study and results begin to suggest some evidence-based best practices for implementing open-ended modeling problems in engineering science courses. For example, while the five students who were interviewed were asked to evaluate their models of the bridge, the other 41 students in the course did not necessarily have this opportunity beyond the second author’s debriefing discussion with the whole class. Therefore, we recommend that students be given time to discuss their model with other students as an opportunity for evaluation. When giving students this opportunity, they could also be asked to specifically compare their model’s completeness, accuracy, and approximation to reality in the frame of the course and in the frame of the real world. We recommend this in-class discussion because research has shown that self-assessment is an important component of teaching mathematical modeling to students [10], and that metacognition is known to be a highly effective practice for developing conceptual understanding [29].

One of the ideas we are continuing to think about as we revise the structure and implementation of these problems is how to grade the students’ work. Grading closed-ended parts of the OEMPs is easy when these parts occur first (as in our OEMP2), because all students will get the same answer. However, grading closed-ended parts of the OEMPs become more difficult when they occur at the end, as all students have a different model and therefore a different solution. Furthermore, grading the open-ended parts of an OEMP is challenging because as we show in the analysis of students’ solution paths, there were answers that were thorough and there were answers that were just sufficient. While our goal would be to have all students analyze and generate a solution like Oliver’s to OEMP2, that will not happen unless we create a more structured problem. Our emphasis in assigning these problems is not to reward a student points based on whether their answer was “good” or “bad,” “correct” or “incorrect.” Instead, our aim is for students to engage in the process of justifying the decisions and assumptions they have made. When our students enter the workplace, their supervisor won’t give them step-by-step instructions for analyzing a system; rather, they will have to develop a method, determine if it is
sufficient themselves, and justify this decision to their supervisor. *Our goal is to have students practice engineering judgment, not perfect engineering judgment.*

We have collected another semester’s worth of student data in the Winter 2019 semester, when the second author once again gave two OEMPs to the students in his mechanics of materials course. The Winter 2019 OEMPs were similar to those analyzed in this paper, but themed around an airplane to relate to the course’s discipline of aerospace engineering. For more details about the Winter 2019 OEMPs, please see our companion paper [20]. As in the data described in this paper, we are once again interviewing and surveying students. Additionally, we are requesting copies of students’ assignment to textually analyze, and we are recording groups of students during the in-class discussions. These data will allow us to continue analyzing how students exhibit productive beginnings of engineering judgment in even more depth.

References


Appendix I. Interview Protocol

Thank you for participating in this study. Before we begin, I want to remind you that you may skip over any questions you do not wish to answer, or withdraw your participation at any time. Do you have any questions?

What pseudonym would you like to use for this study?

For engineering science courses:

You were assigned this problem to do for homework in class. Can you walk me through how you approached the problem?

What references did you use when approaching this problem?

How did you develop the model?

How long did you spend on this problem?

Tell me why the way you modeled this problem is complete enough.

Tell me why the way you modeled this problem is accurate enough.

Tell me why the way you modeled this problem is an acceptable approximation to reality.

Tell me why the way you modeled this problem is the best model?

Tell me how this problem compares to other kinds of tasks you have been asked to do in [course name].

How did this problem make you feel?

Did you expect to do a problem like this in [class name]? Why or why not?

Tell me how this problem compares to the tasks you’ve been asked to do in your core aerospace courses.
Tell me how this problem compares to the tasks you’ve been asked to do in your other engineering courses.

How does this task compare to your vision of an ideal learning task in an engineering course?

How did you do on this problem? Approximately how did you score?

In 7 to 10 years, if you were to teach [class name], would you assign open-ended problems. Why or why not?

Tell me about the answer checker. Do you like it?

Background Questions

How many years have you been studying at the [university name]?

Did you transfer into the [university name] from another university or institution?

Have you had an internships or co-ops that have to do with engineering?

Tell me about some of the other courses you’ve taken in the Aerospace department.
  - Have you taken Aerospace [course number] and [course number]?
  - How do you see [the professor’s] class relate to [course number] and [course number]?

Anything else you’d like to tell me?