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Board 414: Understanding and Scaffolding the Productive Beginnings of Engineering Judgment in Undergraduate Students

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Understanding and Scaffolding the Productive Beginnings of Engineering Judgment in Undergraduate Students

Abstract
This work presents the first year of work on a project addressing the productive beginnings of engineering judgment in undergraduate engineering students. In particular, we discuss a new research question about how open-ended modeling problems (OEMPs), which engage students in engineering judgment, foster the growth of conceptual knowledge. Because OEMPs are open-ended with multiple answers, they are different from the typical well-defined "textbook" problems given in engineering science courses where students learn canonical mathematical models and apply relevant formulas to find a single correct answer. By looking at the conceptual gains that result from assigning an OEMP, we aim to convince other instructors to create and assign open-ended questions. More practice using engineering judgment will give students experience with engineering judgment before receiving their engineering degree. Ideally, this will increase the number of graduates prepared for real-world engineering application.

Introduction
In many courses required for the engineering curriculum, students complete "textbook" problems that require following a standard procedure to apply relevant equations to solve [1]. These problems are well-defined with one single correct answer that typically can only be reached through one solution path. While these problems regularly fulfill the curriculum requirements, they do not necessarily prepare students for work as an engineer outside of academia [2], [3], [4]. Ethnographic studies of engineers in the workplace show that well-defined problems like these are not encountered in the engineering profession; rather, professional engineers solve ill-defined, complex problems in which the core engineering practice is not the calculation of the answer but the modeling of the problem [5], [6], [7], [8]. Solving these ill-defined problems requires engineers to develop and use mathematical models, which is the practice of *engineering judgment*. While engineering judgment develops with time and experience in the profession, we argue that engineering students must be given opportunities to start developing this practice, what we call the *productive beginning* of engineering judgment [9], [10], [11]. They need to encounter situations in their undergraduate education where they are compelled to approach and model a problem without stringent guidelines, analogous to those they will encounter in the engineering workplace.

Our design-based work is concentrated on the simultaneous investigation of student thinking, assignment scaffolding, and the interaction between the two. In the engineering workplace, a strong sense of engineering judgment and an understanding of engineering concepts is vital for success in the field. In the real world, engineering is about having enough conceptual knowledge to understand a problem and apply the correct calculations for that problem. This required level of conceptual understanding is greater than students can demonstrate in solving a typical textbook problem. However, when students can successfully model a problem, make appropriate assumptions, and justify those assumptions, it shows a deeper level of conceptual understanding. Specifically, our multi-institution, collaborative team seeks to answer four research questions:

Student thinking

1) In what ways do undergraduate engineering students display the productive beginnings of engineering judgment?
2) In what ways does solving open-ended problems with a focus on engineering judgment help students learn engineering concepts?

Assignment scaffolding

3) What assignment scaffolding supports students in developing the productive beginnings of engineering judgment?
4) What assignment scaffolding makes students' productive beginnings of engineering judgment (or lack thereof) visible to instructors?

Pre-Grant Work

We have been developing and studying open-ended modeling problems (OEMPs) since the Fall of 2018, when the second and third authors created and studied the first OEMP in the third author's aerospace mechanics of materials course [12], [13]. Between 2018 and 2023, we performed a series of studies, interviews, and analyses. Our first analysis focused on 34 interviews with students who completed an OEMP in their statics or mechanics of materials course. In this analysis we identified, categorized, and described moments of the productive beginnings of engineering judgment by expanding and building upon Gainsburg's [7] eight practices of engineering judgment. We developed the Engineering Modeling Judgment (EMJ) Taxonomy, which characterizes four productive beginnings of engineering judgment: making assumptions; assessing the reasonableness of assumptions, outputs, and models; deciding when and how to use technical tools; and deciding when to override mathematically calculated answers [14]. These four main sections encompass a total of 15 different codes that we use to identify students' emerging judgment.

Current Work

In our first semester of the project, we collected data to address RQs 1 and 3 by assigning a new OEMP to a junior-level fluid mechanics course. This OEMP is a pipe system optimization problem. Students need to design a system that can deliver water from a lake to a greenhouse while minimizing cost and avoiding specified red zones. Students need to use their knowledge of pipe flow to choose a type of pipe while considering size, roughness and cost. This course represents a class level and course topic that we have never studied before. We are currently examining interviews with students after they completed the OEMP in which they were asked about their processes and methods on the OEMP. We are also assessing student performance on conceptual questions related to the topic of the OEMP.

Another major task of the first semester of the project has been the creation of RQ2, which was not part of our original project proposal. Our pre-grant data and analyses have allowed us to establish our first version of the EMJ Taxonomy, which we will be able to apply and further refine throughout our project. Therefore, we have made good progress in understanding the productive beginnings of engineering judgment (RQ1) and we have broadened our focus to collecting data to demonstrate other ways OEMPs aid students' learning. Our goal, captured in RQ2, is to collect data on how students learn conceptual knowledge that is required to solve the assigned OEMP.

Motivation for Research Question 2
The motivation for this new RQ2 came from survey data from students who had completed an OEMP in the past three years at six different universities. The data contains responses from students surveyed in three statics courses (Gold, Purple, and Maroon Universities), four dynamics courses (Onyx, Green, Maroon, and Purple Universities), one upper-level structures course (Red University) and two undergraduate/graduate courses (Purple University vehicle dynamics and thermo fluid design). Students were presented with the question, "The open-ended problem helped improve and reinforce my understanding of concepts taught in [statics/dynamics/aircraft structures/road vehicle dynamics]." and were prompted to report how they related to this statement on a 5-point Likert scale (strongly agree, agree, neutral, disagree, or strongly disagree).

As Figure 1 shows, the majority of respondents generally agreed that they gained conceptual understanding from completing their OEMP and only a small number of respondents disagreed that OEMPs helped their conceptual gain. Out of the 292 responses across the 12 courses surveyed, approximately 65% of individuals selected "agree" or "strongly agree." Comparatively, a small number of individuals, approximately 12%, did not agree that OEMP's helped with their understanding of the concepts. Furthermore, 23% of participants did not have a strong opinion.

Reviewing this data showed our research team that students believe OEMPs help improve and reinforce their understanding of concepts taught in engineering science courses. We have also heard this belief from instructors who implement OEMPs [15]. With this information, our research team developed a new research question to help better understand *how* OEMPs affect conceptual understanding: In what ways do solving open-ended problems with a focus on engineering judgment help students learn engineering concepts?

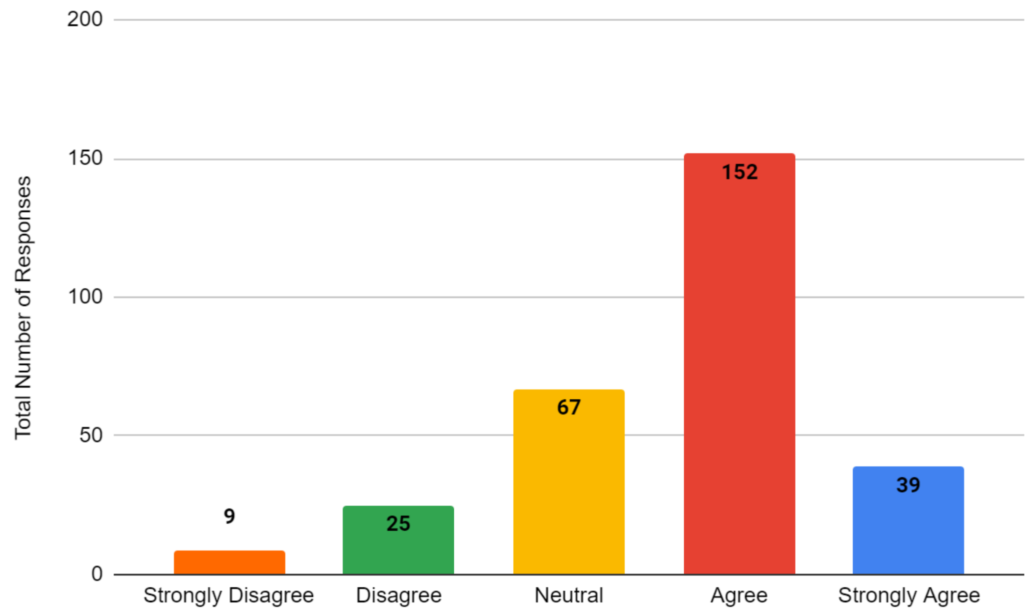

Figure 1: Aggregate student responses to the question, "The open-ended problem helped improve and reinforce my understanding of concepts taught in [course]"

Future Investigations into Research Question 2

With this new research question, we are investigating how OEMPs encourage the use of engineering judgment and reinforce conceptual understanding. We have begun collecting data for this research question in the junior-level fluid mechanics course that used its first OEMP in Fall 2023. In addition to examining interviews with students after they completed this OEMP, we are assessing student performance on conceptual questions related to the topic of the OEMP. During the interviews, students were asked about their processes and methods on the OEMP followed by two conceptual multiple-choice questions. These questions tested the student's knowledge of two topics used in the OEMP: the relationship between density and velocity, and the definition of boundary conditions.

To further test conceptual knowledge of pipe flow and gather a higher number of responses, an optional extra credit assignment was given to the students which had three multiple-choice questions and two conceptual problems. The first conceptual question consisted of an oddly-shaped container where students had to demonstrate an understanding of equilibrium conditions. The second question tested the understanding of pressure differentials and their relationship to mass flow rate. In this question, two identical pipes with fully-developed laminar flow have two different mass flow rates. The mass flow rate through the second pipe is twice that of the mass flow rate through the first pipe. Students were asked about the pressure gradient. The three multiple choice questions tested the understanding of how forces, specifically pressure forces act on surfaces not normal to them. It also tested the understanding of viscous forces. All of these questions then prompted students to explain their answers.

Our research team also gathered responses to a pipe flow test question on the final the previous year (when students were not assigned the OEMP) and this year (when students completed an OEMP). The final exam question was given to the students in a standardized test format allowing an equation sheet and given a set amount of time. The test question was designed to test the conceptual understanding of the overarching concepts encompassed in the course curriculum.

Our research team is in the process of analyzing the above data we collected in the fall to see if there is a connection between students' work on the OEMP and their answers to the exam question and the conceptual questions in the interview and extra credit assignment. We do not yet know which method will be most effective in uncovering student thinking, so we will also explore other ways to measure students' conceptual understanding.

Conclusions and Future Work

This ongoing study delves into how open-ended modeling problems (OEMPs) foster the productive beginnings of engineering judgment and how to best scaffold these practices within the OEMP to most effectively display these productive beginnings to professors. In addition to these questions, we have recently added an investigation into the conceptual understanding of engineering material when practicing with OEMPs. This new research question has been motivated by student survey results and instructor feedback. Future plans include developing a faculty development workshop that will explain how to design an OEMP, why they are beneficial to students' education and development as an engineer, and how to implement them in the classroom. The goal of this workshop will be to encourage professors to use open-ended problems in engineering science courses and give their students an opportunity to practice engineering judgment. With this, we can begin to understand all of the ways in which students develop as engineers from solving these types of problems.

Acknowledgements

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