Results from Understanding and Scaffolding the Productive Beginnings of Engineering Judgment in Undergraduate Students (RFE)

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Introduction

Mathematics is a necessary part of engineering, but engineering encompasses a great deal more than just doing calculations. An engineer must use their *engineering judgment* to fully understand a design space, simplify a system for analysis, choose inputs and boundary conditions for an equation, decide when (and if) to trust calculations, and make the final decision [1], [2], [3], [4]. All of this is still required in our increasingly automated world where software tools and generative artificial intelligence can quickly perform calculations.

The problem with engineering education is that many *engineering science courses* taken in students' sophomore and junior years focus on calculations without engineering judgment. In these courses, students often complete well-defined "textbook" problems that involve finding and applying relevant equations to find the single correct solution. This is important content, but students also need to be given opportunities to develop their engineering judgment in the context of realistic engineering problems, which feature incomplete information, multiple correct answers, and multiple conflicting constraints and requirements [5], [6].

Our multi-institution design-based RFE project addresses this gap and engages students' engineering judgment in engineering science courses. Over the past three years, we have helped instructors to design open-ended modeling problems (OEMPs) to engage their students in engineering judgment, and we have investigated student thinking, assignment scaffolding, and the interaction between the two in the context of these OEMPs. Specifically, we seek to answer three research questions:

On student thinking:

- **RQ1)** In what ways do undergraduate engineering students display the productive beginnings of engineering judgment?

On assignment scaffolding:

- **RQ2)** What assignment scaffolding supports students in developing the productive beginnings of engineering judgment?
- **RQ3)** What assignment scaffolding makes students' productive beginnings of engineering judgment (or lack thereof) visible to instructors?

RQ1. Taxonomy of Emerging Engineering Modeling Judgment

In May 2025, we published an article in the *Journal of Engineering Education* on a taxonomy of emerging engineering modeling judgment [7]. This article represents the culmination of years of data collection, analysis, and writing. One of the contributions of this paper is to define the concept of engineering modeling judgment. Engineering judgment has been studied by a number of researchers, although there is no singular definition of the concept. Generally, engineering judgment is taken to mean informed decision-making in open-ended, dynamic engineering problem-solving situations [1], [2], [3], [4]. However, when authors talk about "engineering judgment," they can be focusing on anything from the entire design process [3] to technical communications [8] to mathematical modeling [9]. To situate our work in this context, we identify our focus as *emerging engineering modeling judgment*. "Modeling" denotes that we are focused on the ways in which students use their engineering judgment to design and use mathematical models in analysis and design. Furthermore, because mathematical modeling is understudied in engineering education research, our paper has another contribution in describing how mathematical models are composed of a *theory of behavior*, which describes the behavior of the object being modeled, and a *representation*, which describes the physical properties of the specific object. As with engineering judgment, there are a number of different names used in the literature for our idea of a theory of behavior—"concepts" [10], [11], "physical principles" [12], "first principles" [13], or just "models" [14], [15].

The second adjective we use in our specific engineering judgment focus is "emerging," which indicates that we are looking at undergraduate students as developing engineers. Engineering judgment is related to—or synonymous with—expertise, and so one cannot expect students to display engineering modeling judgment as practicing engineers [1], [2], [3], [4]. However, students can engage in practices that are similar to expert practices, but at an age-appropriate level [16], [17]. With more education and experience, students continue developing these emerging behaviors.

The research contribution of our article in the *Journal of Engineering Education* outlined our Emerging Engineering Modeling Judgment (EMJ) Taxonomy, a significant and novel result of our research. To develop the EMJ Taxonomy we analyzed 34 interviews with students who had completed open-ended modeling problems. The EMJ Taxonomy details 4 types and 15 subtypes of emerging engineering modeling judgment (Table 1). It builds off of the work of Julie Gainsburg [9] and draws connections with work from research on how students make assumptions [18], [19], [20] and assess reasonableness [19], [20], [21], [22], [23]. Fundamentally, the EMJ Taxonomy demonstrates that undergraduate engineering students have the ability to engage in engineering judgment, a practice that is deeply related to expertise, at an age-appropriate level. Our OEMPs did not explicitly instruct students in EMJ, and so they show that students can be encouraged to engage in EMJ through purposeful scaffolding.

The EMJ Taxonomy can also be used by engineering education researchers to study students' EMJ in other contexts. We have begun this work by creating a new taxonomy that captures how students' project teams exhibit EMJ. This research, which has been submitted to the *International Journal of Technology and Design Education*, is based on semi-structured interviews with 11 undergraduate students on 9 different extracurricular project teams at the University of Michigan. We coded transcripts of these interviews with the EMJ Taxonomy, allowing for the creation of new codes and the adjustment of the codebook language. This Emerging Engineering Modeling Judgment on Project Teams (EMJ-PT) Taxonomy has 4 types and 18 subtypes (Table 1). Of these subtypes, five have a code description edited from the original EMJ Taxonomy, two were created from splitting one EMJ subtype, and two were newly-created from the interview data. The differences between the EMJ and EMJ-PT Taxonomies occur because project teams work on design that is more open-ended than coursework-based OEMPs, are organized into subsystems where students need to collaborate and coordinate modeling, and are responsible for building an actual system.

Table 1. Comparison of the two emerging engineering modeling judgment taxonomies we have developed as a part of this research project.

Code	EMJ Taxonomy	EMJ-PT Taxonomy
EMJ 1	Making assumptions	Making assumptions about the representation or theory of behavior
EMJ 1a	Making an assumption with no justification	*No change*
EMJ 1b	Assumption considers the user, client, or manufacturer	*No change*
EMJ 1c	Assumption makes the model more realistic, accurate, representative, or typical based on the student's research or experimentation for the class	Assumption makes the model more realistic, accurate, representative, or typical based on the student's research or experimentation done after having the problem in front of them
EMJ 1d	Assumption makes the model more realistic, accurate, representative, or typical based on the student's personal lived experience outside the classroom	Assumption makes the model more realistic, accurate, representative, or typical based on the student's personal lived experience prior to having the problem in front of them
EMJ 1e	Assumption makes the model solvable	*No change*
EMJ 1f	Assumption makes the model easier to solve and/or simplifies the model	*No change*
EMJ 1g	Assumption does not affect the output of the model	*No change*
EMJ 1h	Assumption models what the student thinks is the worst-case scenario	*No change*
EMJ 1i	*Not present*	Assumption is not made by the student, but provided by another person on the team (a current teammate, an alumni, a team Wiki)
EMJ 2: Assessing reasonableness		*No change*
EMJ 2a	Assessing the reasonableness of assumptions that the student made	Assessing the reasonableness of the representation assumptions that the student made
EMJ2aii	*Not present*	Assessing the reasonableness of the theory of behavior assumptions that the student made
EMJ 2b	Assessing the reasonableness of the output of the model	*No change*
EMJ 2c	Assessing the reasonableness of the model as provided by the instructor in the problem	Assessing the reasonableness of the model as provided to the student (e.g. by an instructor, another team member, a previous year's team, etc.)
EMJ 3: Overriding a calculated answer		*No change*
EMJ 3a	Overriding a calculated answer with no justification	*No change*
EMJ 3b	Overriding a calculated answer considering the user, client, manufacturer, or safety	Overriding a calculated answer considering the user, client, manufacturer, or safety, or future margin
EMJ 4: Using technology tools		Implementing the model
EMJ 4a	Using a technology tool to help with analysis or computation	Using a technology tool to perform analysis or computation
EMJ 4b	Assessing their use of the technology tool	Assessing their use of the technology tool that performs analysis or computation

EMJ 4c	*Not present*	Considering the information gained from a model vs. the complexity and resources required to create and run the model (e.g. time, money)

RQ2. Scaffolding of Open-Ended Modeling Problems (RQ2)

Research

Our approach to understanding scaffolding [24] support for OEMPs has examined both *planned scaffolding*, or assignment documents and presentations professors give to their students, and *interactional scaffolding*, or in-the-moment interactions with students during office hours or feedback given when students are turning in assignments [25], [26].

We examined planned scaffolding of the Pool Lift OEMP as assigned by one professor [27] by examining the assignment structure as well as the instructor's thoughts on the process through an interview. The two undergraduate researchers on the project, and authors of the paper, decided to further explore the interactional scaffolding that occurs during the Design Requirements review process that includes five in-person submissions by each student team. During the Fall semester, the four-person research team recorded over 28 hours of interactions between the professor and students and took observational field notes.

The research team listened to each recording and determined if there were instances of interactional scaffolding about engineering judgment (at times interactions were about correcting mathematical errors). This eliminated 5.5 hours of recordings. Transcripts with clear audio and engineering judgment were transcribed and then listened to and coded by a member of the team. Two undergraduate research assistants open-coded six hours of data, followed by a more focused coding of interactional scaffolding tools based on the work of Tharp and Gallimore [28]. We have identified patterns in the ways the professor assesses the students' knowledge and either increases or decreases her scaffolding based on students' abilities (much like the Zone of Proximal Development [29]). We are currently preparing a manuscript to report these findings.

Dissemination

To disseminate our work on designing OEMP scaffolding, we wrote a manuscript framing OEMPs as a form of project-based learning (PjBL) that allow engineering instructors to cover multiple different ABET Student Outcomes in an engineering science course. This manuscript has been submitted to the *Journal of Civil Engineering Education*. The manuscript is grounded in a list of seven curricular elements of PjBL [30], and for each dimension of PjBL we introduce a guiding concept or framework from research, giving the reader background knowledge about how we approached the OEMP design. We then discuss the details of OEMP scaffolding related to that PjBL dimension and describe how this scaffolding allows the instructor to achieve ABET Student Outcomes. In particular, we focus on outcomes 2-8, which are not typically addressed in engineering science courses.

As an example of the structure of this manuscript, we discuss the PjBL dimension of assessment and evaluations. The OEMP scaffolding is designed around the guiding concept of achievement goal theory, which outlines three goals one can have: mastery goals focused on learning the material, performance-approach goals focused on demonstrating good performance in comparison to others, and performance-avoidance goals focused on avoiding bad performance in comparison to others [31]. Of these, a mastery orientation has been found to have widespread positive effects on student learning [32], [33]. To encourage students working on an OEMP to develop a mastery orientation, the OEMP is graded with a focus on students' justifications. Instructors look for students describing how they employ their engineering judgment, rather than solely grading students' final answer. Requiring students to justify their work emphasizes ABET Student Outcome 3, which addresses communication skills, and encouraging students to adopt a mastery orientation emphasizes ABET Student Outcome 7 on lifetime learning [34].

Responsive Teaching During Open-Ended Modeling Problems (RQ3)
To answer RQ3, we are analyzing the transcripts of interviews with five faculty members using deductive coding guided by the concept of *responsive teaching*. In this concept, instructors elicit student thinking around a topic, notice the disciplinary substance of students' thinking, and respond in real time to support students' disciplinary behaviors [16]. Coding centered around examples of *disciplinary substance*, instances where the instructors discuss students engaging in engineering judgment and related engineering practices.

In our initial codebook, the code of Eliciting was originally defined as "elicit student thinking around a particular topic." However, the interviews reflected the iterative and cyclical process of responsive teaching. Instructors would elicit, notice, and respond to students, and then re-elicit to continue engaging with students. To capture this, the parent Eliciting code was broken up into two subcodes: a student-focused "elicit to prompt student thinking or reflection" and an instructor-focused "elicit to understand student thinking." Instructors described using homework assignments and groupwork to prompt the initial eliciting. These deliverables, including but not limited to designs, mockups, models, free-body diagrams, and design review forms, provided students with structured opportunities to document their work along with their reasoning, assumptions, and design changes. The interviewees explained how this format allowed them to focus their face-to-face instruction on noticing and interpreting their students' emerging engineering judgement in order to compare the students' modeling outputs (models and designs) with their thought processes and assumptions. Some of the results from the data include the instructor noticing times when students' assumptions, equations, and/or results did not reflect real-life phenomena, when students had design problems stemming from conceptual misunderstanding of the class content, and when some students overcomplicated the problem to a point where it was not solvable within the bounds of the course.

Finally, instructors acknowledged concerns and challenges associated with implementing responsive teaching. Results showed primary concerns with scalability and workload balance. Interviewees described their attempts to design and scaffold their assignments in order to provide students with an adequate number of feedback opportunities without overwhelming students with deliverables.

Conclusion
This design-based research project has produced fundamental knowledge of emerging engineering modeling judgment and interactional scaffolding, as well as evidence-based guidelines for the design and facilitation of Open-Ended Modeling Problems (OEMPs). We are currently working on finishing manuscripts capturing our analysis of interactional scaffolding (RQ2) and responsive teaching strategies (RQ3). We are also working on ways to make our example OEMPs and scaffolding guidelines public and easily-accessible so that other instructors can build off of them to better introduce engineering judgment in their own engineering science courses.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grants No. 2313240 and No. 2313241. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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