Making Assumptions and Making Models on Open-ended Homework Problems

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Making Assumptions in Open-ended Homework Problems

Abstract

This research paper presents a study of students making assumptions and discretizing elements when solving an open-ended modeling problem (OEMP) in a sophomore-level statics class. OEMPs are homework problems with no single correct answer that ask students to mathematically model a real-world object. Our analysis focuses on two elements of engineering judgement: making assumptions and discretizing elements. We found some students made assumptions to model the real-world object as closely as possible, while other students made assumptions to create a simpler mathematical model. Furthermore, students did not always justify their decisions completely or clearly. Implications of our work include revising the OEMP prompt to engage students in more authentic assumption making and continuing to assign open-ended problems to give students experience with engineering judgement, thereby better preparing them for their professional engineering careers.

Introduction

Mathematical modeling is an essential skill in engineering. In almost all of their technical core, or engineering science, courses, engineering students learn how to construct mathematical models of natural phenomena. Constructing a mathematical model to analyze a system is an important practice of engineering, particularly for ill-defined engineering problems where the beginning of the modeling process requires an engineer to make assumptions (e.g. modeling an oddly-shaped beam as a prismatic rectangle) and discretize elements (e.g. modeling the individual forces of people on a bridge as a distributed load over the entire span) to simplify the problem. Making assumptions and discretizing elements are part of *engineering judgment* [1]. Engineering judgment is defined as “judgment to make a final call on the reasonableness of the analysis or design” (p.287, [1]). In practice, engineering judgment can be equated to expertise, which is developed as an engineer spends more time in the profession.

This study is part of a larger project studying students’ productive beginnings of engineering judgment in mathematical modeling [2],[3]. Previous studies by Swenson [4] and observations in teaching by Johnson led us to conclude that engineering science courses need to provide undergraduate students with more opportunities to practice modeling ill-defined problems in order to prepare them for the problems they will encounter as professional engineers [5]. We developed Open-ended Modeling Problems (OEMPs) to create opportunities for students to develop and practice engineering judgment. OEMPs are designed using four principles: 1) they are situated in a real-world context; 2) they are open-ended, meaning there is no correct answer; 3) students apply “canonical” mathematical models that are learned in class; and 4) students practice engineering judgment. The data presented in this paper comes from one specific OEMP assignment in which students in a sophomore-level statics course analyzed the iWalk2.0 hands-free crutch.

Our work on OEMPs began by figuring out how to implement the problems in the classroom and then conducting research in the first class to complete an OEMP through interviews with five students and a survey with the whole class. Research questions included how OEMPs gave students opportunities to practice engineering judgment [2] and students' affective responses to the OEMPs [3]. This current paper is the first attempt at expanding the number of students whose problem-solving processes we can analyze by looking in-depth at the assignments they turned in.

In this paper we focus our analyses on one specific aspect of engineering judgment [1]--how students made assumptions when solving an OEMP. The OEMP students were asked to solve revolved around the structure of the iWalk2.0, a device meant to replace crutches by attaching to the lower leg and leaving the users hands free. Students were asked to mathematically model the iWalk2.0 during use with a free-body diagram, and then determine the material and size of the main supporting member in the structure. Identifying students' assumptions is critical for two reasons. First, making assumptions in an important aspect of engineering judgment; therefore, students are required to make and justify assumptions in an OEMP. Analyzing students' assumptions will be helpful in refining this specific OEMP assignment and developing general guidelines for writing OEMPs on any topic. If multiple students are not making reasonable, well-justified assumptions, this suggests that the problem should be redesigned to provide more scaffolding that helps students make more realistic assumptions or more explicitly prompts them to write out their justifications. Second, having students metacognitively reflect on their own assumptions is an important factor in their development of engineering judgment. By understanding what assumptions students are making and the impact these have on design, instructors can highlight productive beginnings of engineering judgment and help students understand when they have made assumptions that are not reasonable or well-justified. Therefore, we ask:

RQ1: What assumptions and discretizations did students make about human gait, applied weight, and the iWalk2.0 structure?

RQ2: What implications did these assumptions and discretizations have on students' free-body diagram and mathematical model?

Theoretical Framework Background or Literature Review

In many texts, engineering judgment is synonymous with expertise. Davis [6] discusses that in order to develop expertise engineers need to "solve problems, participate in discussions, work in labs, write reports, and otherwise practice the discipline, under the supervision of those who are adept at it" (p.790). Gorman [7], in his summary of the types of knowledge engineers need to have, defines judgment as "the knowledge of when a particular piece of information is useful, when it is effective to apply a particular skill, and when specific skills and information need to be combined" (p.329). Our framework of engineering judgment is based on a study of two structural

engineering firms and how these engineers used mathematical models as they designed buildings [1]. Analyzing the engineers' work, Gainsburg outlines seven categories of engineering judgment:

- EJ1. Determining what is a good or precise enough calculation or estimation
- EJ2. Marking assumptions or simplifications to be the bases of mathematical models
- EJ3. Overriding mathematically "proven" results
- EJ4. Determining appropriate uses of technology tools
- EJ5. Assigning qualitative factors (e.g. soil type) and applicable condition for selecting formulas
- EJ6. Overriding official building codes
- EJ7. Discretizing (grouping elements to reduce the number of types to be designed)
- EJ8. Determining what elements or conditions were "typical" (representative) for the structure

(p. 486-487, [1])

In previous work [2] we examined interviews of students solving an OEMP and found students practicing all of the above except EJ3 and EJ6. This is not surprising, given that these categories require years of experience, and are typically not taught in undergraduate engineering courses. In other words, no engineering instructor would teach her students to override building codes!

For this study, our team wanted to start expanding the number of students whose problem-solving processes we can analyze, moving from conducting a few retrospective interviews to examining the submitted work of every student in the class who consents to participate in the research. Second, our team wanted to increase our understanding of engineering judgment by examining the beginnings of one or two of the specific categories Gainsburg [1] outlines in the paper. In this specific study, we decided to focus on the process of students making simplifying assumptions (EJ2) and discretizations (EJ7), which we view as one specific type of assumption. Making assumptions is a key step of mathematical modeling and is needed to apply mathematical models based on scientific laws to real-world situations [8]. As Edwards and Hamson [9] point out, "the ultimate success or failure of our model will very likely depend on whether we make an apt choice of assumptions" (p.73). Edwards and Hamson (1990) go on to identify three different types of assumptions that one might need to make:

1. Assumptions about whether or not to include certain factors
 2. Assumptions about the relative sizes of terms or the relative magnitudes of the effects of various factors
 3. Assumptions about the forms of relationships between variables
- (p.73)

Engineers and engineering students are required to learn how to make these types of assumptions within the context of their specific discipline. For example, in fluid mechanics one learns that in order to use Bernoulli's equation one needs to make the assumption the fluid is incompressible, inviscid, and applied along a streamline. Yet, when we ask students to practice using these scientifically-based models in the context of a course, we rarely ask them to consider and evaluate whether these assumptions hold for the given problem. Instead, the problems are written so that they inherently (and often implicitly) conform to the assumptions underlying the models that students are to apply.

In current engineering practice, analysis and simulation software packages require an engineer to make assumptions, such as how to constrain a system being analyzed. Engineers also need to understand the implicit assumptions built into their software tools to understand where failure points could occur and how to interpret the results. Therefore, any analysis begins with the student or engineer explicitly and/or implicitly making assumptions and it is important students begin practicing this as undergraduate students.

There are very few studies in engineering that explicitly look at assumption making, especially because engineering students are so rarely assigned open-ended problems. In a study of undergraduate material science engineering students solving open-ended homework problems [10] researchers found making assumptions was one of the most difficult aspects of solving the problem for students. They also found students with some workplace experience to make more reasonable assumptions, which aligns with the idea that developing judgment takes experience. In a study of professional structural engineers, Gainsburg [11] observed engineers debating the inclusion of different assumptions and justifying how the assumptions accurately represent reality.

The importance of discretizing elements and making assumptions is an essential part of model-making for which current engineering courses and curriculums provide little practice for students. We have designed Open-ended Modeling Problems (OEMPs) to engage students in this practice, among others, and this study is another step in the development and assessment process for these OEMPs. Specifically, this study examines how second year engineering students make assumptions and discretize elements when given an open-ended mathematical modeling problem with implications for the design of future homework problems.

Methodology

This study was conducted at a small private university located in the Northeast. Students were recruited from the sophomore-level mechanical engineering (ME) statics course. Statics, along with another course on design and manufacturing, are the first two ME-specific courses taken at the university, and most second-year ME students are enrolled in both of these courses. Both sections of statics were taught by the fourth author. The goal of the OEMP in this course was for

the students to engage in the two categories of engineering judgment that align with our research questions: making assumptions or simplifications to be the bases of mathematical models (EJ2), and descritizing (EJ7). Other learning objectives were to:

- Practice drawing free-body diagrams that conform to Newton's third law.
- Compare a simplified mathematical model to the real world device

The OEMP revolved around the iWalk2.0 hands-free crutch and was written by the fourth author. The iWalk2.0 is an assistive device used to replace crutches for people with below-the-knee injuries (Figure 1). The main advantage of the device is giving the users freedom to use their hands while doing their daily activities. The overarching task for the OEMP was to make a simplified model of the iWalk2.0 crutch and perform an analysis of the vertical bar that connects the knee pad to the base. Students were invited to use and/or measure an iWalk2.0 purchased by the third author to have a physical artifact available to students during the semester.

Figure 1: iWalk 2.0 Handsfree Crutch [12]

When a person walks with the iWalk 2.0, its base touches the ground and supports both static forces, such as the weight of the person or friction along the ground, and dynamic forces, such as the person's heel strike force. The students' primary task was to find the proper material and diameter for member AB (Figure 2) that would be strong enough to support a 125 kg person with a height of 175 cm while the device is used to walk on a flat surface. The instructor gave the students a simplified 2D model of the device (Figure 2) and instructed them to make certain assumptions to scale down the openness of the problem and lower the amount of time required to solve the problem:

- Straps at D, C, and E are looped cables with zero tension during stance phase.
- Member CK is connected to EC and AB through smooth pins at C and K
- Member DN is welded to member EC at N.
- Member AB has a circular cross-section and is massless.
- Human body segments can be considered as rigid members.

Figure 2: Simplified 2D model of iWalk 2.0

While these five assumptions were implemented by the instructor, students were explicitly asked to make two important assumptions on their own about the structure of the iWalk2.0:

1. The type of connection the device makes with the ground at point A “which best describes the real scenario” (text from the assignment).
2. The type of connection at point B, either a smooth pin or a welded joint.

In order to solve the OEMP, students were implicitly required to make two additional assumptions about the weight of the 125 kg person using the iWalk2.0, and one additional assumption about the weight of the iWalk2.0 members:

3. The amount of the person’s weight that loaded on the iWalk2.0.
4. The location where this weight acted on the iWalk2.0, and if the weight was discretized as a point force, multiple point forces, or a distributed load.
5. The stance phase of walking that put the highest load on the device.
6. If and how the weight of the iWalk2.0 members (except AB, which was assumed to be massless) should be taken into account.

After making these assumptions and drawing a free-body diagram, the students performed a static force analysis to calculate the force and stress in member AB. The set of equations for this static force analysis were the students’ mathematical model of the iWalk2.0. This mathematical model was then used to determine a material and diameter of member AB that was strong enough to support the person. After performing these calculations, students were asked to justify their answer, assess if their answer was reasonable, consider what other forces or moments could be added to the analysis, and decide how the analysis would change if it were not on a flat surface.

Data Collection and Analysis

Students were asked to submit their OEMP solutions electronically. A graduate student researcher de-identified the scanned homework and delivered them to the first and third authors. Of the 75 students enrolled in the course, 62 consented to having their written assignment responses analyzed in this research. A handful of students also consented to participate in retrospective interviews. Seven students were randomly selected from those who consented and contacted by e-mail to set up an interview. Four students were interviewed by the first author and recorded over an online conferencing platform. The interviews were transcribed and analyzed looking specifically for statements on assumptions and discretization.

Authors 1 and 3 analyzed how each student made the six explicit and implicit assumptions that were left to the students: the type of connection at point A, the type of connection at point B, the amount and discretization of the person’s weight, the stance phase, and the weight of the iWalk2.0 members. They divided the assignments and independently analyzed about 10

assignments each before comparing and contrasting their results. They discussed each of the assumption categories and narrowed the analysis to the three categories of assumptions that had a significant influence in the construction of the free-body diagram and the mathematical model, and the selection of a material and diameter for member AB. These assumptions included 1) the stance chosen, 2) the amount and discretization of the person's weight, and 3) the type of connection chosen at point B.

Data

We present how the 62 students made assumptions (RQ1) followed by an explanation of how those assumptions had implications for the construction of their free body diagram and mathematical model (RQ2).

Stance

Forty-one of the 62 students (65.6%) explicitly assumed the highest load on the iWalk2.0 was during midstance, which is the phase of walking where only one foot is touching the ground while the other foot passes it. The remaining 21 students did not specify their stance choice in writing, but an inspection of their free-body diagram indicated they chose midstance. Despite being a common assumption, midstance is not actually the phase of walking where the highest load is exerted on the iWalk2.0. Biomechanic studies indicate that the most force exerted on the leg comes between the heel strike and midstance, and again between midstance and toe-off [13]. As these students had little or no biomechanics background, it is not surprising that they made this assumption. Yet, the advantage to choosing midstance is the simplicity of only having to consider a normal force acting vertically at point A, and not a reaction force with x- and y-components.

Weight and Force

Forty-four students, or 72.1%, assumed the full weight of the person (125 kg) was on the iWalk2.0. The remaining 17 students had various fractions of the person's weight that they justified. Students mainly discretized the load in two ways, with 43 students (70.5%) applying the person's weight as a single point force and 7 students (11.5%) applying the weight as a distributed load. The remaining 11 students (18%) had various other methods including two different-sized point loads along member EBC (Figure 2), or one point load on member EBC and one on member DN. How to consider the person's weight was the most open-ended part of the problem as there were many ways to discretize force. These assumptions did have an impact on students' free-body diagrams and their mathematical models. However, these choices have no impact on students' final answers for the material and diameter of member AB. For example, modeling the person's weight as a distributed load over EBC is the same as modeling the weight as a resultant point force with a magnitude equal to the area of the distributed load and a location equal to the centroid of the distributed load.

Joint B

The assumption that had the largest impact on students' mathematical models of the iWalk2.0 was the choice they made about the type of connection at point B. Thirty-one students (50.8%) chose point B to be a smooth pin joint and 29 students (47.5%) chose point B to be fixed or welded. One student did not specify the connection and it was unclear to researchers examining their mathematical model what they had assumed. If students assumed joint B to be welded, their analysis included an internal reaction moment at point B, and therefore a more complicated mathematical model. In fact, this assumption made the problem statically indeterminate, and therefore unsolvable unless students neglected the diagonal member CK. If students assumed joint B to be a smooth pin, there was no moment at point B and thus a simpler mathematical model. In this scenario, both CK and AB were in compression. Because member CK was not part of the analysis, the primary impact of students' choice for the joint at B was affecting the magnitude of the force in AB.

Solving for Member AB

After students used their free-body diagram and mathematical model to determine the force on member AB, students used this information to solve for the diameter of the member and select a material. 43 students (70.5%) worked with a known material and calculated the diameter of AB. 15 students (24.6%) used the measured diameter of the iWalk to calculate a yield stress and used that number to select the material. 3 students (4.9%) used both methods.

Discussion

The goal of assigning OEMPs in an engineering science course is for students to engage in the beginnings of engineering judgment while using mathematical models taught in that course. The iWalk2.0 OEMP discussed in this paper asked students to engage primarily in two categories of engineering judgment: making assumptions or simplifications (EJ2), and discretizing elements (EJ7). In this paper, we examined how students made decisions in these two areas and the implications these decisions had for the construction of students' free body diagram and mathematical model. The goal of this analysis is to determine how students were engaging in the productive beginnings of engineering judgment while building a mathematical model and responding to questions that were posed in the assignment. The primary goal of this analysis is to improve the construction and scaffolding of OEMPs to further engage students in open-ended analysis problems and not "plug and chug" textbook problems [14].

We are unsure why students overwhelmingly chose to assume midstance for their analysis, as students generally offered little or no justification. Did students pick midstance because they believed that's where the most weight was applied? Or did students choose that stance because it was an easier analysis? To engage students in more engineering judgment, we must change the prompt to explicitly ask students to consider and justify their choice of stance. An alternative way to increase engagement in the productive beginnings of engineering judgment would be to

get rid of the given assumption of the analysis taking place on flat ground and have students choose and justify whether flat, uphill, or downhill ground would give the highest load on the iWalk2.0.

Students' assumptions and discretizing of the person's weight were the most varied category. Yet, in the current analysis, modeling the person's weight as a distributed force or a point force has no impact on students' final answers for the material and diameter of member AB. This is actually an important concept for students to understand. The problem only asked students to find the internal force of member AB, which was not the member on which the person's weight was applied, which was member EBC. To stress the fact that representing the person's weight as a point force or a distributed force can be equivalent, a post-OEMP assignment or discussion could have asked students to specifically assess whether the discretization of the person's weight influenced the results for member AB. Or, students could have been asked to analyze the internal forces, internal stresses, or deflection of member EBC, which *do* depend on the way the person's weight is discretized. So if the problem had asked students to analyze member EBC, students' assumptions and discretizing of the person's weight would be very impactful. Such a question could be posed in the next iteration of the OEMP, asking students to compare the impact of different weight discretizations when calculating the material and diameter of certain members. Either additional follow-on activity would help students to understand that more complicated and physically realistic discretizations (such as modeling the person's weight as a distributed load) are not always beneficial.

Students' assumptions about joint B are the most interesting of all instances of engineering judgment in this problem. In the actual iWalk 2.0 device, member AB is rigidly attached to the horizontal member (EBC). Therefore, if one were to realistically model the iWalk2.0, joint B should be modeled as a fixed or welded joint. Yet, only 47% of students modeled it in this way. In prior OEMP work analysing interviews of students evaluating their mathematical models [2], we saw students considering the accuracy or completeness of their models through two different *frames*. Framing [15],[16] is the set of expectations one has about a situation. Like in Koretsky and Nolen's [17] study of senior chemical engineering students, in our prior study we found students to evaluate their OEMP models in either the "school world" or the "engineering world." For the students, the school world and engineering world encompassed different expectations that were not always congruent. For example, a model could be accurate enough in the school world if the math was correct but *not* accurate enough in the engineering world because there were certain factors missing from the analysis.

This tension between trying to satisfy both worlds was evident in the interview data. A student reflected on this tension between worlds and remarked about his process and those of his peers "Compared to other students that I've seen...less of my assumptions were cop-outs....I kinda feel

a little bit in between the mix between students who did it as accurately as possible and the students who basically were like...no forces are even on this diagram.”

In this study, students’ *framing* of the OEMP could explain the choices they made for joint B. Students who modeled B as a welded joint most likely made this decision to be realistic as possible, despite the more complicated mathematical model and the need to make additional assumptions so the problem would be solvable and not statically indeterminate. These students most likely framed the problem in the context of the engineering world, and approached the problem like they were engineers at iWALKFree (the company that makes the iWalk2.0). This was the case for one student interviewed, saying “We assumed it to be welded....We would have both the X, Y, forces and the moment, but if we had thought of it as a pin, for example, there won’t be any moment with it. So we made, when we made these assumptions, we wanted to be as realistic as possible.”

The other 50.8% of students who modeled the joint as a smooth pin most likely understood this simplified the mathematical model. These students most likely framed the problem in the context of the school world, and approached the problem as students needing to get their homework done. For a different student interviewed, this was the case. They reported “I assumed that was fixed initially because it seemed more realistic, and I realized it would be harder to solve if it was fixed because there would be an extra moment that would have to be fixed. So I just said, let’s just call it a pin and then I only have to worry about like an X and Y force. So that was another assumption I had to change to eventually get to my final answer.” Students had the agency to model the problem in whichever way they see fit and were not told to model the problem in the most realistic way possible, or were penalized for not doing so.

While the students’ choice of assuming a smooth pin at point B to simplify the problem might not seem like a good engineering decision, literature shows us that practicing engineers *do* model structures in a physically-unrealistic way in order to simplify the mathematical model. In Gainsburg [1], she illustrates how an engineer decided to model a spandrel beam with a uniform thickness despite in reality having two different thicknesses along its length. This decision was made to greatly simplify the analysis. Later during the design process, the engineer had an hour long debate with a colleague about this choice. They concluded that keeping the beam at one thickness was insufficient and needed to remodel the beam. Yet, what this episode illustrates is the engineers considered the validity of their assumption and its effect on their model. With little to no experience making assumptions, students most likely did not make these same considerations. There were at least two students who wrote out their thinking process and considered both options--a smooth pin and a welded joint--and set up mathematical models for both scenarios. As practitioners and researchers, this insight into students’ thinking was helpful in better understanding the problem solving process and judgment students were engaged in. In order to better engage students in these considerations, we need to continue to modify the OEMP

description and the required answers and justifications to encourage students to document their thinking process.

One of the major goals of assigning OEMPs is to allow students to engage in ill-defined problems as they will when they are practicing engineers [5]. During the interviews, two of the four students expressed frustration with the ill-definedness of the problem and lack of a clear, “right” answer. Responding to the question “How did this (OEMP) problem make you feel?” the student stated “I was just very frustrated and the assumptions made me even more frustrated, because I don’t like making assumptions, because the reason why I’m an engineer is because there’s an answer or, like, you don’t have to assume a lot of things. That’s why math makes sense, because it’s like, there’s one answer.” Responding to the same question, another student stated “At first I was pretty frustrated...I guess overwhelmed by the idea that like, my answer is right...a reason I like engineering was because I liked math and science better than, like English and stuff, because there could always be like one right answer, and that’s how it worked and you either got it right or you got it wrong and like, that was that.” In a previous study of students solving open-ended homework problems [10],[18], students similarly found the ill-definedness and uncertainty of a correct answer challenging, overwhelming, and uncomfortable.

These student reflections, while only from two novice engineers, demonstrate the importance of including ill-defined problems in the engineering curriculum. While it is absolutely valid these students would feel frustrated or anxious when encountering their first or second ill-defined problem, their idea that engineering problems are math problems, and therefore have one right answer does not match what students will experience in their engineering careers. Previous studies have shown junior and senior students see ill-defined problems as workplace problems and well-defined problems as school problems [10], so it could be these students have not had enough professional experiences to have developed a sense of the engineering field yet. One of these two students interviewed seemed to understand this idea. When asked “If you were to teach ME 20, would you assign an open-ended problem?” the student responded, “I feel like students...this is something that most students should go through because, as I’m hearing open-ended problems are kind of what people do in the engineering world anyway.” We argue the importance of including OEMPs or other ill-defined problems in the curriculum to develop engineering judgment and the ability to deal with vague problems and other non-engineering metrics of success [19] to better prepare students for their professional careers.

Conclusions and Implications

This study examined an open-ended modeling problem (OEMP) given to second-year students in a statics course. To solve the OEMP, students were explicitly and implicitly required to make assumptions and discretize elements to determine the needed diameter and material for a particular bar in the iWalk2.0 hands-free crutch. We synthesized three assumptions that students made: 1) the stance at which they chose to perform their analysis, 2) how the person’s weight

was distributed onto the crutch, and 3) how they modeled the joint between the bar being analyzed and the knee rest of the iWalk2.0. Our analysis of these assumptions suggests that some students made decisions that simplified their analysis, and other students attempted to best represent the conditions of the real world.

Our results show that this OEMP needs revision in order to engage students in more authentic assumption making, and therefore better engage with the productive beginnings of engineering judgment. First, we want students to engage in some research about the relationship between force and gait instead of just making the common, but incorrect, assumption that the largest ground reaction force is during midstance. Second, we want to create a prompt asking students to examine the effect (or lack thereof) of different discretizations of the person's weight. This will help students to understand, for example, when it is necessary to consider the person's weight as a distributed load and when it is sufficient to consider weight as a point force. Third, our team would like to further investigate why students modeled joint B in the ways they did and add a question explicitly asking students to justify their assumption. Beyond providing us with this information, we hope that this will cause students to reflect on their framing of the assignment, and how this framing influences the assumptions they make. These iterations on the problem statement will hopefully increase students' exposure to and experience with engineering judgment and better prepare them for a career in engineering.

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