Designing and Implementing Open-Ended Problems in Engineering Science Courses

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Abstract: This article describes the process of implementing a form of open-ended problems, called open-ended modeling problems (OEMPs), into undergraduate engineering science courses. It explains the need for open-ended problems in the undergraduate engineering curriculum, the common troubles with assigning open-ended problems, and a "how-to" guide for implementing OEMPs into any class or teaching style.

Author Keywords: Open-ended problems; Problem scaffolding; Engineering judgment

Introduction

The undergraduate civil engineering curriculum comprises many engineering science courses, which are courses that focus on foundational concepts and mathematical formulas. This curriculum consists of statics, dynamics, and structural and fluid mechanics courses where students are typically assigned closed-ended textbook problems that are written out-of-context and have one single correct answer. These closed-ended problems are nothing like what professional engineers see in industry, which are contextualized, ill-structured, open-ended problems that require assumption making, mathematical modeling, and conceptual problem solving (Gainsburg 2007). This dichotomy between engineering science courses and real-world engineering has been noted before (Gainsburg 2007; Johnson and Swenson 2019; Jonassen 2014), along with other gaps between students and industry professionals. These gaps include professionals documenting more specific assumptions than students (Ahmed et al. 2021) and focusing to "fine-tune existing models" instead of starting from scratch each time like a student would (Bissell and Dillon 2023). Thus arises the need for more open-ended problems in engineering science courses in the civil engineering curriculum; engineering courses should show the use of concepts in real-world engineering applications instead of solely focusing on the

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use of mathematical equations. Engineers need to do more than just solve well-defined problems; they need to create, manipulate, interpret, and apply mathematical models to understand and predict the behavior of systems and processes (Gainsburg 2007).

Open-ended problems have been found as useful for students to gain knowledge on course topics through “productive failure” (Kapur 2008) and to learn how to make assumptions that reduce the amount of variables and simplify problems (McNeill et al. 2016). Through various ethnographies and case studies of professional engineers it has been described that reasoning about assumptions (such as simplifications of the design conditions) is an essential skill for the field and for safe design practices (Barner et al. 2022; Gainsburg 2006, 2007; Henry 1994). However, throughout their educational careers students are rarely required to make important assumptions while problem solving until their senior design courses, where they struggle with applying the mathematical analysis from prior coursework to particular design solutions (Cole et al. 2012).

The art of assumption- and simplification-making aren’t skills that can immediately be adopted. Because it is so vital to engineering, there needs to be an emphasis on inculcating these practices into the curriculum earlier. A big implication from an investigation of problem-solving processes between students, faculty, and practicing engineers in civil engineering found that making students familiar with ill-structured problems beginning in their freshman year could better prepare them for their future professional careers (Akinci-Ceylan et al. 2022). The benefits of active learning in general has also been cited in the literature (Freeman et al. 2014; Gallagher and Savage 2020). So then the question arises of what is holding back the implementation of open-ended problems? Not nearly enough are being assigned; one study found that 55% of STEM classrooms are dominated by “didactic” instructional practices (i.e., passive lecturing requiring little to no student engagement) (Stains et al. 2018) and another noted that while over 80% of engineering educators are aware of the benefits of active learning techniques, their adoption rates were just shy of 50% (Borrego et al. 2010). The effectiveness of open-ended problems are clearly seen, so now our attention shifts to implementation strategies.

Looking at the college level, many professors simply don’t have the time to implement long, complex problems into their classes when short, simpler ones are considered acceptable. Most faculty are not rewarded for investing time in being innovative in their teaching (Lee 2000), so it makes sense for them to apply the most time-efficient teaching methods even if they are less effective in achieving student outcomes (Jonassen et al. 2006). The current lack of open-ended problems in courses of nearly all STEM disciplines can be attributed directly to these difficulties: faculty have insufficient class time, lack of preparation time, large class sizes, or inexperience with implementing the problems (Boylan-Ashraf et al. 2017; Dancy and Henderson 2010; Finelli et al. 2014; Froyd et al. 2013). These concerns towards implementation are certainly valid, and this paper aims to alleviate them and promote the use of one particular type of open-ended problem, called open-ended modeling problems (OEMPs), by providing a step-by-step guide for properly scaffolding (i.e. developing and implementing) them.

Background

OEMPs are assignments that have no correct answer and ask students to create a model to solve a problem in a real world context (Swenson et al. 2019). These OEMPs are designed to be implemented in the heavily mathematical engineering science courses mentioned previously. A slew of real-world engineering applications are placed towards the end of the civil engineering undergraduate curriculum in the form of lab, senior design, or senior capstone courses. This has mainly been done through experiential learning, such as incorporating Kolb's cycle into a Building Information Modeling (BIM) project planning capstone course (Zhang Jingxiao et al. 2019), and project-based approaches, such as a project design course to introduce students to the infrastructure life cycle (García-Segura et al. 2023). The exposure to more open-ended problems are great in these courses, as students are nearing their entrances into industry, but OEMPs attempt to expose students to them earlier to allow better preparation for advanced learning in senior course work. There have been several attempts to implement more open-ended problems that help students better understand the real-world implications of their work into civil engineering science courses before, some recent ones being a project-based learning study in sophomore-level statics and dynamics courses (Zhang 2023), an analysis of introducing 3D printed models into a sophomore-level structural engineering course (Dart and Lim 2023), an investigation of attempts to improve students' evaluation of reasonableness in a junior-level mechanics course (Hanson 2022), and the development of instructional modules designed to give clear insights of real-world concept applications in a junior-level introduction to geotechnical engineering course (Seo and Yi 2023). OEMPs seek to accomplish many of the same goals as these existing implementations, but do so by offering a more generalized and structured way to allow instructors to integrate them nicely into their existing class systems, teaching styles, and desired learning objectives.

Another evidence-based approach for explicitly incorporating real-world mathematical modeling into undergraduate engineering science courses is Model-Eliciting Activities (MEAs). MEAs are designed to "simulate authentic, real-world situations that small teams of 3-5 students work to solve over one or two class periods. The crucial problem-solving iteration of an MEA is to express, test and revise models that will solve the problem" (Hamilton 2008). In an MEA, students are provided data and are asked to create a mathematical model of the situation as well as a process or procedure to communicate their understanding of the complexity and limitations of their model (Zawojewski et al. 2008). MEAs have been popular in the engineering curriculum for some time and have been shown to even change faculty members' instructional beliefs towards a more student-centered view of teaching (Moore et al. 2015). The biggest difference between an MEA and an OEMP is that MEAs encourage the generalization of mathematical data whereas OEMPs require the application of formulas learned in class to a complex, real-world object. That is why we have developed our own type of problem; research on modeling-focused engineering judgment has not found evidence of practicing engineers engaging in this "generalizing," or "detecting patterns in data and expressing them as mathematical rules or formulas. [...] Generally, the engineers were expected to adhere to the rules of the industry, not invent their own” (Gainsburg 2007). OEMPs are designed to have students complete problems related directly to what they’ll see in industry, enabling them to use the concepts learned in class and apply it to real-world, ill-defined problems that will require additional assumptions and simplifications to be made.

Purpose

Our research team has implemented OEMPs at nine institutions over the past five years with the mission of reducing the gap between engineering courses and industry. These OEMPs have been implemented in mainly statics classes, but it has also been found that they are transferable to other courses such as dynamics (Swenson et al. 2022). The focus of the OEMPs has been on improving engineering judgment in students, which Gainsburg described as using “judgement to make a final call on the reasonableness of the analysis or design” (Gainsburg 2007). We have researched students’ ability to practice the productive beginning of engineering judgment (PBJ), resulting in the basic framework seen in Table 1.

Table 1: Productive Beginning of Engineering Judgment Framework

Productive Beginning Code	**PBJ Example**
PBJ1. Making Assumptions	A student treats a person walking across a bridge as a point mass instead of a distributed one to make calculations simpler
PBJ2. Assessing Reasonableness	A student realizes the center of gravity they found for a beam is on the very end, so they recheck their assumptions and calculations
PBJ3. Using Technology Tools	A student runs a programming script to figure out where the largest stress occurs on a truss to speed up the solving time
PBJ4. Deciding to Override an Answer	A student finds the column size that can mathematically hold up a building is smaller than they expected, so they make it larger to be safe

This focus on students' ability to practice engineering judgment is due to prior research showing that engineering judgment cannot be taught directly, but through practicing situations that require it (Borrego et al. 2010; Engle and Conant 2002; Jonassen 2014; Lave and Wenger 1991). Focusing more on the application of these skills has potential to improve students’ understanding of complicated topics in the civil engineering curriculum, such as the close relationship between design and construction (Edmondson and Sherratt 2022), the principles of sustainability in design (ABET 2022), the “bootstrapping” process of structural engineering (Gainsburg 2007), and the real-world implications of topics such as building codes (Barner and Brown 2021) – just to name a few. Inculcating OEMPs into curricula inherently forces students to engage with engineering judgment and understand the real-world application of their course topics.

During our own research and implementations we have surveyed students at the end of each class that assigned an OEMP. The surveys consist of Likert scale questions about their experience and opinions of the OEMP, a section about their emotional pathways while completing the problem, and open-ended questions to allow for feedback to the professor and the research team. In Figure 1 below, you can see the survey results from the spring semester of 2022. This survey was given to students from six different courses that had implemented OEMPs into the class.

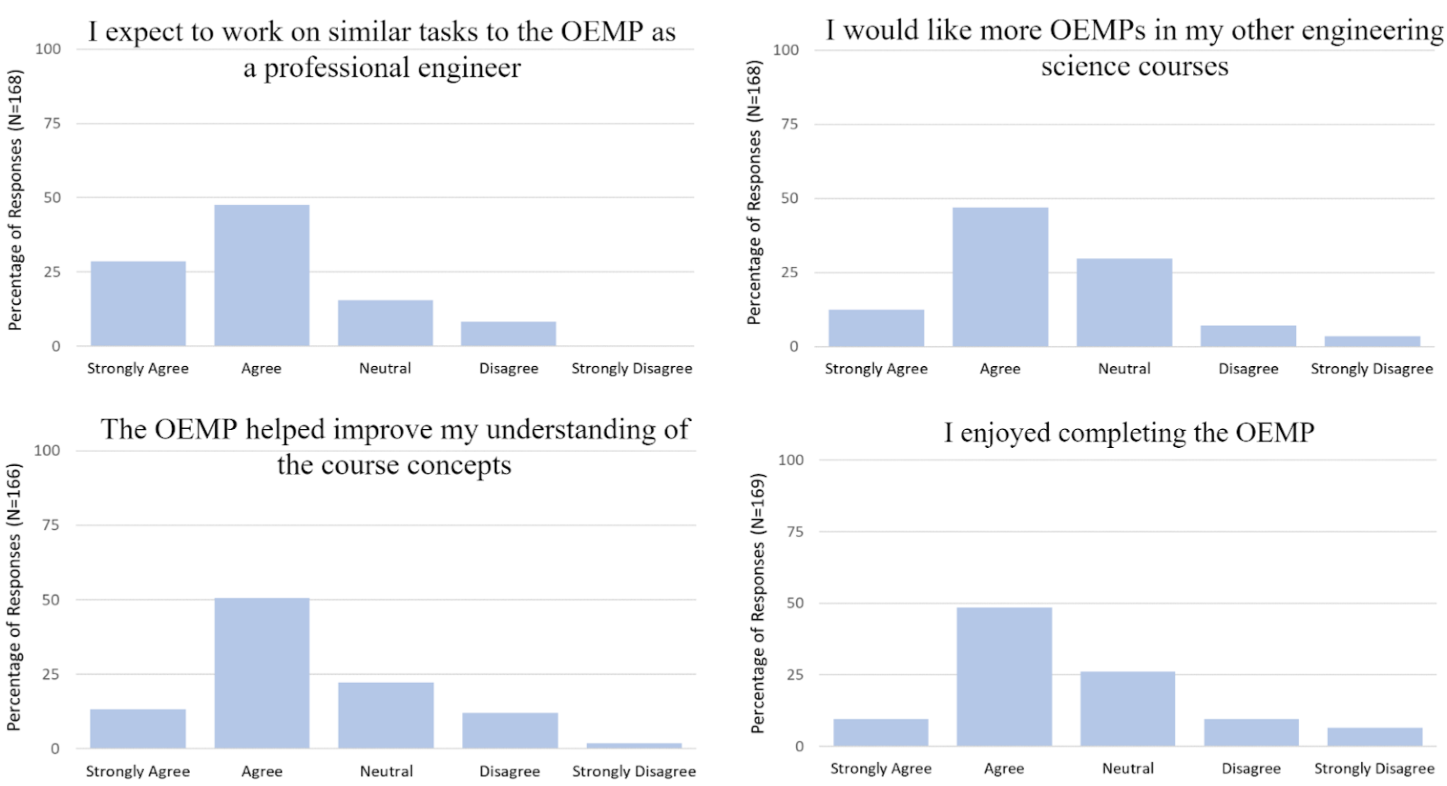

Figure 1: Student Survey Data on OEMPs from Spring of 2022

These surveys provided relatively positive feedback on the OEMPs. The surveys show that the majority of students expect to work on these ill-defined problems as a professional engineer and that they want more of them in their other classes, which complements much of the literature on the importance of open-ended problems for engineering students. The surveys show that the majority of students believed the OEMP helped improve their understanding of the course concepts, which is great because the OEMP can be used as a solid teaching tool to enhance the instruction of the course. Lastly, the surveys show that the majority of students enjoyed completing the OEMPs. This is not necessarily something we envisioned when assigning the problems, but it indicates that undergraduate engineering students enjoy completing problems that relate directly to the engineering they'll be doing in their careers. We recognize that these surveys have some non-response bias and that there are various factors that go into how a student receives an assigned problem in class (teaching style reception, busyness outside of class, etc.). But from the data and feedback we are able to collect, the OEMPs seem to be serving their purpose and providing students with the real-world engineering experiences they otherwise wouldn't have until later in their college careers.

From our own implementations of OEMPs we have found many "best practices" that help avoid the typical issues that arise when assigning open-ended problems. Most of these revolve around the concept of scaffolding the OEMP and properly planning the implementation of it in class. Scaffolding relates to how an instructor helps a student accomplish a learning objective that they otherwise could not do on their own, McKenna describes it as "the process by which a teacher, mentor, or more knowledgeable person helps a learner achieve a task that would otherwise be out of reach" (McKenna 2014). It was also described by Reiser as "a delicate negotiation between providing support and continuing to engage learners actively in the process" (Reiser 2004). These open-ended problems are ones that most students have not seen before, so the scaffolding of going from textbook problems to ill-structured ones is extremely important (Jonassen 2014). Scaffolding will be the main theme of this paper, which we consider as both the design of the problem and the support of the instructor to encourage the productive beginnings of engineering judgment through informed, or responsive, teaching practices (Crismond and Adams 2012; Hammer et al. 2012; Johnson et al. 2017). Our research team has written a couple conference papers (Johnson and Swenson 2019; Treadway et al. 2021) that describe useful tips for assigning OEMPs, but this paper is designed to be a comprehensive "how-to" guide for OEMP implementation.

How to Design and Implement an OEMP

In this section we describe how to best implement an OEMP in your class, grounded on our design-based research which focuses on assigning OEMPs and analyzing student and professor feedback. A basic flowchart of how to construct an OEMP can be seen in Figure 2, which shows the main pieces of assigning an OEMP in a class: Baseline and assignment specific plans, creation, implementation, and iteration. The following sections align with the flow chart and describe each piece in more detail, with heavy emphasis put on the implementation and scaffolding phase of OEMP development.

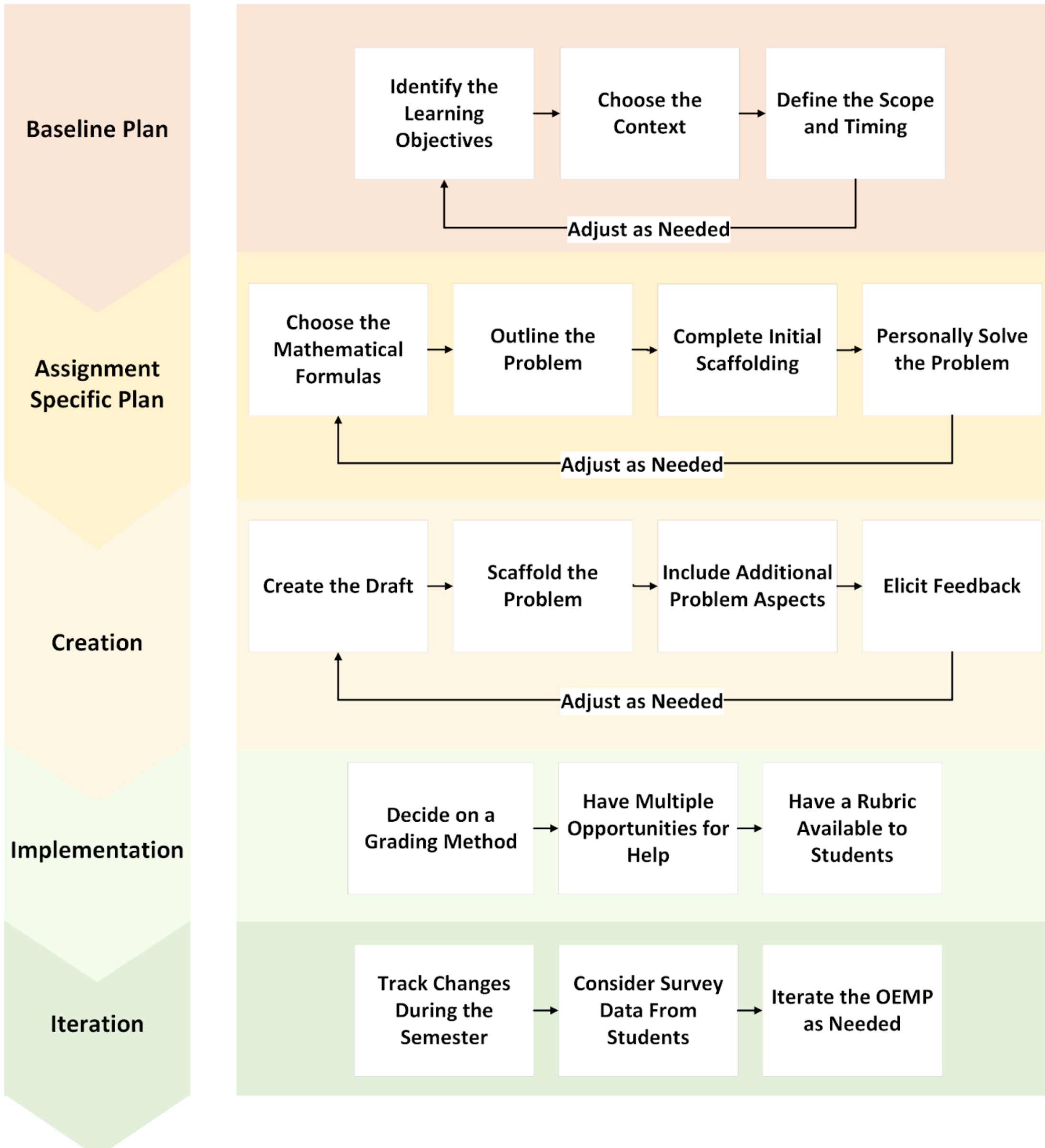

Figure 2: Flowchart of Designing and Implementing an OEMP

Baseline Plan

The first step in creating an OEMP is to **identify the learning objectives** and **choose the context** for the problem. This seems simple in practice, but it is the decision that all of the following steps will revolve around, so it is of utmost importance to solidify these right from the start. To begin thinking about your learning objectives you should consider what concepts from class the OEMP will cover and what engineering judgment will be elicited through the OEMP. An example of a learning objective that we have covered through an OEMP already is having students be able to formulate and solve the equations of equilibrium. As far as engineering judgment goes you can refer back to Table 1, but essentially all OEMPs should require students to make assumptions or justifications and later reflect on the reasonableness of both their methods and final answers. Remember that the goal of an OEMP is to reinforce concepts from class while also helping students build engineering skills, so it is vital to make sure a topic from class is covered by the OEMP.

After you have chosen what concepts the students will learn while completing the OEMP, you should now consider a context for the problem. When we refer to the context, we are talking about the real-world model or system that students will be modeling. The first step will be to identify a real-life scenario that students can relate to, and that would have some sort of practical application to their later careers as engineers. Consider problems related to your students' majors, school, local attractions, or current events. Some examples that have been used in the past are an airplane landing gear (related to aerospace engineering majors), a hypothetical bridge between two university buildings (related to the school), and an actual slide at a local park (related to a local attraction). At the end of the day students should be modeling an object that actually exists, and that they can see (whether in real life or through pictures and videos) and/or touch and use. This allows students to collect data on the real object and compare it to their own model and results, both of which assist students in making and assessing their assumptions and results. Not all contexts will be able to achieve your desired learning objectives and engineering judgment, so make sure to keep that in mind and potentially alter the context a bit to be able to achieve the most important goals.

If the OEMP is not well-planned then it can be dangerously easy to get thrown off schedule or run into logistical class issues while giving the assignment. The best way to avoid this is to **define the scope and timing** of the OEMP from the start and plan for any potential problems that you envision may arise. First, you will need to decide on the 'P' in OEMP. Of course the 'P' stands for 'Problem,' but because OEMPs are so flexible it is possible for them to be delivered in various formats. A list of these formats can be seen in Table 2, which details the required time, description, and pros/cons of each one. A common theme we have seen during our OEMP implementations is that students will get out what they put into them, so going all in on OEMPs will provide the most benefit to your students. Of course there are many other restrictions that could get in the way of that, for example if you are working within a teaching team or have strict requirements for what tasks students need to accomplish then you will have much less flexibility than someone who is free to implement new problems into their course curriculum. But in the end we believe that any exposure to OEMPs will improve the students' engineering judgment, thus you should implement whatever format works best for you and your class.

Table 2: Options for OEMP Delivery Format

Delivery Format	Time Required	Description	Pros/Cons
Example in Class	Low	Instructor will complete an OEMP for the class and/or give students one to complete on their own or in groups during class time.	Pros: Takes one class period and requires little preparation / grading Cons: Students are only exposed to OEMPs once, spend a class period on an OEMP and not lecturing
Homework Problem	Medium	A 2-3 week long OEMP that covers concepts which have already been learned, will be mostly done out of class – individually and/or in groups.	Pros: Reinforces students' learning of topics while introducing assumption and simplification making Cons: Will need to account for the homework that is typically assigned during these 2-3 weeks
Checkpoint Quizzes	Medium	Consistent (bi-weekly or monthly), short OEMPs that act as a check for student learning. Simple enough for students to complete in the allotted amount of class or take-home time.	Pros: Students will be consistently exposed to OEMPs during the semester Cons: Will need to come up with a quality OEMP for essentially all course topics throughout the semester
Class Project	High	One large OEMP that serves as the primary source of assignments / homework. Should be broken down into 2-3 week deliverables related to the overall OEMP.	Pros: Students will be fully immersed in a real-world engineering project Cons: Need to restructure the class to revolve entirely around the OEMP
Midterm or Final Exam	High	An OEMP extended over a week or so in place of a time constrained exam. Should provide ample other types of OEMPs throughout the semester so students are familiar with solving them.	Pros: Eliminates exam-anxiety, high importance placed on OEMPs. Cons: Need to be paired with another OEMP delivery format to get students familiarized, a lot of pressure put on writing a good, solvable OEMP

Low time commitment OEMPs would require no grading, but still allow for the development of some simplification and/or assumption making skills through independent or group work during class time. Medium time commitment options still allow you to maintain the same relevant structure of the class, along with giving students a bit more exposure to real-world problems. High time commitment options will let you give students more time throughout the entire semester to develop their engineering judgment and are great if you want to make the OEMP a larger part of your class. Again, these are all just implementations that we have seen done before or we envision working well, so feel free to attempt any or add additional delivery formats that may not be listed but you know will integrate well into your class and teaching style.

Next, you need to decide on the method of completion; determine whether students will work individually, as a team, or a combination of both. We do recommend including some sort of team aspect to the OEMP, due to the opportunity it affords students to justify their assumptions and explain themselves to fellow peers which creates a great environment for practicing engineering judgment. However, we do recognize that there are positive and negative externalities with any group project, such as one group member taking too much control or dealing with group members who are not as dedicated to working on the assignment. Lastly, you need to choose when the assignment will be given in the course, how much time students will have to complete it, and how quickly feedback is needed on each part of the OEMP if you are doing a multi-step one. Timing is important because you will want to make sure that the OEMP is assigned soon after topics are taught, while students still have enough knowledge from lecture to complete all parts of it. Because this is such an unfamiliar experience for the students, which will induce more anxiety than regular homework problems, it should be noted that an extended period of time and more office hours options may be needed for students to properly complete the problem – but further advice for handling this can be found in the implementation section.

Assignment-Specific Plan

Once the baseline plan is set, or at least thoroughly thought about, then more detailed parts of the OEMP can be fleshed out. The first step of planning the specific OEMP involves three parts: deciding what part of the system the student will analyze, what mathematical formula they will use, and what variables from the system they will calculate. That may seem like a lot, but it is typically easiest to start with the second item from those three; you should first **choose the mathematical formulas** that the students will work on from your class. For example, will they be finding the maximum load that an object can hold? Or approximating a moment of inertia? From there it is pretty obvious that the three main aspects of the question will be having students model the chosen part of the system, find what equations to write, and then calculate the specified variables. All three of these aspects are related, so if you decide upon one, then the other two should inherently be determined.

From this initial model it is then best to create a simple **outline of the problem**. This is to get an idea of what the students will be solving and to make sure it is feasible for them to do before getting heavily involved with the creation of the entire OEMP. The outline should cover the overall design objectives and the intermediate parts of the problem necessary to solve it. This is also the time for you to **complete the initial scaffolding** of the problem, by this we mean your initial planning for supporting students through the assignment. Some things to keep in mind are whether the length will line up with the scope, timing, and OEMP delivery format that you considered previously and if it will be applicable to the method of completion and format that you hope to have the students solve it in. Also start to distinguish between the open-ended and closed-ended aspects of the OEMP, decide where students can just grab an equation used in class versus where they need to make assumptions or simplifications to reach the answer.

Once the outline is done, it is important to **personally solve the problem** to make sure that it will be reasonable to ask your students to complete and to find any issues that may arise. Think about whether the problem is too open- or closed-ended and if it is hitting on all of the learning objectives that you want. Consider the answer you got versus the one you were expecting, look for ways where a student could go awry while solving it. This is just an initial check to see if the idea of the problem is ready to be worked on further; if you think the problem is ready then move on to the creation phase, but if not you can go back and adjust the model, scaffolding, and outline as needed.

Creation

Now that you have the planning done for the OEMP's context, scope, and execution, it is time to **create a draft** of the problem. This is where you take the model that the students will be working on and **scaffold the problem** so that they can properly solve it. This may not be the prettiest at first, but we have plenty of suggestions to help out with scaffolding after the basic problem information and questions are put down on paper.

The first consideration to make while scaffolding is figuring out which parts of the problem need to be simplified and what assumptions need to be made before the students begin. You already decided on what the students will model, now consider how to make that model solvable. If you just throw a real-world problem at the students, it will more than likely be easy for them to get it to an unsolvable state. For example, most sophomore statics courses only teach statically determinate structures while most real-world structures are statically indeterminate. When simplifying a real-world structure there are only a few ways to make it statically determinate, but many ways for it to become statically indeterminate. As a result, students may have a great deal of difficulty getting to a statically determinate model from the beginning on their own. To avoid this, simplify the problem just enough to get it close to a solvable state for the students while still requiring them to employ engineering judgment of their own to solve it. You can also warn them either in class or in the problem statement that it can become indeterminate (or of other problems that may arise) and tell them what to look out for to avoid it.

You also need to break the OEMP into parts in order to provide students with so-called "checkpoints" to keep them on the right path. There should not only be one question on an OEMP; there should be a series of questions that lead the students in the correct direction, while prompting them to reflect on their assumptions, simplifications, and reasonableness along the way to see if they need to change anything. For OEMPs that are multiple assignments long, the checkpoints can be executed in a few different ways because they will occur in between the assignemnts.You can have students do individual problems and then come together as a team to create a better model than any one individual has, you can ask students to reflect on assumptions or simplifications that they made throughout the OEMP (similar to the single problem checkpoints), you can give students time to change or improve their models, you can personally check in with the students or teams to provide help, you can have different teams or students compare their methods with each other, or you can do some combination of any of those. The main point is that students need to be directed during both single and multi part OEMPs, and if you sense them going off-kilter further than you envisioned then that is a tell-tale sign to add additional, more effective scaffolding / checkpoints.

The last consideration to make while scaffolding is what resources you will encourage the students to use. These resources can be anything that give the student information on what they are modeling, such as websites, articles, images, gifs, videos, etc. Unless one of the learning objectives for the OEMP is to have students find information (which it may be!), you will definitely want to either give them high-quality, trusted resources directly or point them to areas where they can easily find the information. By doing this you will prevent the students from finding bad resources or spending too much time researching, and it will also help with grading as the answers will be more similar amongst the class.

There are still some final logistical decisions that can be made to **implement other aspects** into the OEMP. This includes the important step of getting students to reflect on their answer's reasonableness. Assessing reasonableness is one of the four aspects of engineering judgment seen in Table 1, and through these OEMPs we have found that it is one of the easiest to evoke from the students. To get the students to reflect on the reasonableness of their answers you can either just have one of the questions be "How reasonable is your answer?" or you can simply have them justify each of their answers which in turn encourages them to reflect on why their assumptions or simplifications led them there. If your context is a real-world object that students are familiar with, you can explicitly ask them to compare their answer to the real-world object when assessing the reasonableness of their answer. Another option to elicit this type of engineering judgment is to have them think about situations when the assumptions become unreasonable to make. An important note here is that both you and your students should understand that in most cases getting an unreasonable answer does not mean that the math or equation used is wrong, but is because the model is not realistic. It is not required, but a few of the OEMPs have also included things such as presentations, final reports, and peer review assignments. This is really up to your discretion, as it may help achieve some additional course learning objective, other than evoking student reflection, such as memo writing or presenting.

While making this draft, and really throughout the entire process of thinking up and creating the OEMP, you should be considering how open-ended the problem is. There are two extremes that you want to avoid, one is that the OEMP gives little to no direction at all and students can't even figure out how to start the problem, let alone complete the entire thing. And the other extreme is that every student is able to complete it identically to their peers and there's no more assumptions, simplifications, or engineering judgment needed than if they were simply solving a textbook problem.

It is not expected that you write the perfect OEMP on the first shot… or the second… or the third. Different issues will appear each time you develop the OEMP further, or assign it to a new class, or make changes to improve it. However it is still possible, and really your ultimate goal, to get a really good OEMP designed before implementing it in the classroom. The main way to do this is through revising the draft as many times as needed and **eliciting feedback from others**.

First you want to revise it yourself, and by revise we mean to physically work through the problem. This is similar to when you solved it during the assignment specific plan, but this time try to solve each step of the OEMP exactly how the question asks and find any hiccups that come up while doing this. You also want to ask yourself the following questions along the way:

- Are the learning objectives (both class and engineering judgment) being achieved?

  Think about additional topics that may need to be added or further opportunities for students to attempt making assumptions and simplifications.

- Is there too much or too little scaffolding that could cause problems?

  Try to see where you can provide additional support within the problem, or if the problem is too restrictive. Think again about adding further opportunities for students to attempt making assumptions and simplifications.

- Is the final answer that *you* get reasonable or not?

  You shouldn't expect all answers by students to be reasonable, or even close to reasonable – that's something they can reflect on after completing it to improve on their engineering judgment. However, if the answer that you are getting is way off the mark (as in no student will even think it is feasible), it is probably best to think of better simplifications that can be made to give a better answer.

- Is the deadline you have planned appropriate?

  If it took more time to complete than expected, then either parts of the OEMP need to be cut out or the deadline needs to be extended. (And remember that students will certainly need more time than you!) Look for mental blocks that come up and if additional scaffolding can be put in to further help out students.

After you have worked through the problem yourself and can no longer find any issues with the OEMP, you should have others work through the new draft in a relatively similar fashion (asking them the above questions as they solve). It will be useful to have colleagues, graduate student instructors, and students who have taken the class previously all attempt to solve the problem. This step is not meant to be onerous, these helpers don't have to complete the entire OEMP by any means – they can just read through it, do a couple calculations that you may be concerned about, and provide good, quality feedback in a short 60 minute meeting. You should collect their feedback on the solvability, open-endedness, wording, scaffolding, and other aspects of the OEMP to see which parts need improvement. Then from there you can make all of the proper revisions, and then continue to attempt getting as many additional eyes on the problem as possible before implementing it in your class.

Implementation

Now that we've created the OEMP, we're onto the critical part of the process of implementing it into the class. While creating the OEMP you have already considered some important aspects such as timing and scaffolding features, now is when you can put them all together along with some additional considerations to properly implement it. The first step is **deciding on a grading method**; think about how large of a portion of the grade and the class the OEMP will make up. Will it be treated like a typical homework set, or maybe multiple homework sets? Will it be a project all on its own and have a certain percentage of the grade associated with it? How will the time and effort required for it compare to the other parts of the class, and is the weighing of the grade reflective of that? You want the OEMP to be worthwhile for the students to complete, but not a stressful sink-or-swim aspect of their grade. Also check that the OEMP aligns with the topics taught in class to ensure that students will have all that they need to complete the OEMP and that they learned the relevant information reasonably close to the time that the OEMP will be assigned.

Following closely to the timing of the OEMP, you should also consider what will be done both in the classroom and outside of it to support students throughout the process of completing their OEMPs. We recommend telling students about the grading style and pointing them towards a posted rubric – which will be discussed later on – and explaining the differences between the new OEMP and the previous homework problems done thus far. Students may be especially anxious about having to make their own assumptions and simplifications, so it would be a good idea to explain in depth what they need to do and how they will be graded. You should communicate the fact that there is not a single correct answer, and that you are instead looking for justification. Also consider implementing class discussions, time for group work, or even an example problem that requires making assumptions or simplifications around the time that the OEMP is assigned to ensure that students will have enough instruction to properly attempt the problem. It is important that students are receiving support from the instructors, instructional assistants, and other students throughout the OEMP. Providing additional office hours or meeting individually with groups may be needed, in the end you want to **provide multiple opportunities**

for help and feedback during the OEMP as that will increase the students confidence levels and help to best guide them through the unfamiliar problem. It is good to reference the OEMP as a real-world example within weekly lectures when relevant to give students an idea of where the concepts learned in class can be applied. You can also consider providing a small amount of time during a few classes for students to discuss the OEMP and ask questions.

OEMPs have been implemented in classrooms of upwards of 300 students and in ones of as few as 13 students. Obviously the grading is going to look different depending on the amount of students, resources, and time that you have, but the amount of students should not be a barrier when implementing an OEMP. When grading you want to emphasize the justification of answers over correct ones, and make sure students are attempting to make assumptions and simplifications along with reflecting on the reasonableness of their answers. If you have both group and individual parts to your OEMP then it may be easier to only grade the group portion, as grading one assignment will cover up to five students. However, if you do this then you should still do something to ensure that students do the individual portion (such as grading for completion or a simple quiz) as that allows them to participate with their group. For example, in the 300-student statics course that assigned an OEMP, the instructors designed a timed 10-question graded quiz that was implemented in the course learning management software. The quiz contained completely new questions with one correct answer, but used the same mathematical models as the individual OEMP. The instructors believed that if a student did the individual OEMP they would do well on the quiz.

An important aspect of grading the OEMP is to **have a rubric available to students** so that both you and the class are clear on expectations and on how the grades will be assigned. When designing the rubric you will want to prioritize conceptual understanding and the problem solving process. It is way too much work to check that each student got the correct mathematical answer from the model that they created because every student has a different, individual correct answer. So emphasizing the justification of their assumptions and answers is a much better route to go down, and an example rubric that emphasizes this can be seen in Figure 3. This rubric is very general and could be used for your class, or it could be used as a baseline for you to adjust the weights of each part and add or take out anything additionally you would like. The rubric focuses on the students properly attempting the OEMP (so modeling the correct systems and following the solving process taught in class) and on practicing engineering judgment (so making the assumptions required in the problem and justifying those assumptions along with their final answer).

Criteria	Full Credit	Partial Credit	No Credit
Correctly identified and modeled the system in the way that is being taught in class			
Correctly applied the formulas and processes taught in class to each part of the assignment			
Made the proper amount of assumptions/simplifications required from the problem statement			
Gave an answer and commented on the reasonableness of said answer for each part of the assignment			
Justified all assumptions, simplifications, and answers thoroughly when prompted by the problem statement			
Feedback:	Score:		

Figure 3: Generalized Rubric for Grading OEMPs

Iteration

Unforeseen issues are bound to happen, especially if this is the first time implementing an OEMP, but it is important to iterate on an OEMP with some drawbacks instead of completely throwing it out. As discussed, open-ended problems are tough to assign in undergraduate engineering science courses, but OEMPs do not have to be perfect for students to reap rewards. If you give up after your first few attempts at an OEMP aren't perfect then you'll never see the benefits they'll eventually have on your students. A lot of the issues and complaints may be overblown because the students are being put in such an unfamiliar position, so this feedback should not be discouraging but instead be used to improve on future OEMPs. The areas of the OEMP that get the most complaints suggest places for additional scaffolding or breakdown of the problem.

The best way to iterate on the OEMP is to **keep track of challenges throughout the semester** and note the places where the assignment went awry while students completed it. This can simply be done through formative assessment by yourself or your instructional assistants. But in the end the most useful source of feedback is from the students completing the OEMPs. You should have students record how long they spent on each part of the OEMP to gauge where complications occur, individual open-ended problems should not be taking them any longer than

10 hours to complete – it may be useful to also mention that to them. One of the most beneficial forms of feedback is **considering survey data from students**. While implementing our OEMPs so far we have collected many student survey responses (four responses from spring of 2022 can be seen in Figure 1), where we ask them both questions to use for our research and to help improve on the OEMPs each semester. These surveys contain some Likert style questions about different aspects of the problem, a drag-and-drop question about their emotional pathways while completing the problem, and a few open-ended responses asking for any additional feedback on the OEMP, a list of the good Likert survey questions can be found below:

- Evaluating student learning
  - I knew what the expectations were from me while completing the OEMP
  - The OEMP helped reinforce my understanding of concepts taught in this class
- Evaluating group work
  - I enjoyed working with a group on the OEMP
- Evaluating student affect
  - I enjoyed completing the OEMP
  - I'd like to have more open-ended problems like these in my other non-lab / non-design engineering courses

And a couple good open-ended questions to ask are:

- Is there any additional scaffolding (instruction / support) that would have been helpful to get you over any mental blocks you may have encountered?
- Do you have any other thoughts about how the OEMP was assigned in this class?

Again, we want to emphasize that there are struggles and enjoyment with the openness of OEMPs. At the end of the day the purpose of OEMPs are to improve students' capacity and comfortability to work with open-ended problems similar to what they'll be doing in industry. We have found that students have enjoyed these problems, but when they are put in such a new situation they may begin to disfavor them to their familiar closed-ended problem counterparts. This is perfectly understandable and is just a growing pain to implement the OEMPs. You will be able to know what will help improve your class best, so always be willing to **iterate the OEMP as needed**. Ideally you can also work with additional faculty that teach follow-on classes at your school to have them implement their own OEMP in their courses. We have found that completing multiple OEMPs is good because students gain more familiarity and confidence with the open-endedness after the first one and will have better experiences with the additional ones.

Conclusion

The literature and prior research shows the importance of open-ended problems for learning important engineering skills such as assumption and simplification making. However, the majority of the undergraduate civil engineering curriculum consists of engineering science courses that give closed-ended, well-structured, textbook problems. In order to properly teach engineers to have them ready for industry, more open-ended problems need to be implemented. It is understandable why these problems are avoided, as they are challenging to create, assign, and grade, especially for professors who are already squeezed on time. As a result, we have made a way to implement what we call open-ended modeling problems (OEMPs) ino a class without uprooting the structure, time-commitment, or teaching method of it.

OEMPs are flexible enough to be assigned for any sized classroom and can be beneficial to students in any form. At the end of the day OEMPs are a way for students to get an idea of real-world engineering practices, along with a better intuition for when certain assumptions or simplifications can be applied. Too many engineers are being sent into industry with little to no concept for what a reasonable model looks like or with any intuition for making important design decisions. Any amount of application to real-world systems will help engineering students tremendously for later in their careers, and OEMPs are a simple and effective way to help build up students' engineering judgment abilities. Students chose to study engineering for a reason, so having quality engineering-like examples in class will keep them engaged and excited with the important content they need to learn.

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