Student outcomes from enacting agency in open-ended problems

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Abstract

This complete research paper highlights the experiences of students with open-ended problems through the lens of the theoretical construct of agency. We define agency as the freedom to make decisions or take actions towards a self-directed goal. Professional engineers have to enact agency in their workplace on a regular basis in the form of making tradeoffs between constraints and satisfying requirements, selecting and iterating over multiple problem-solving approaches, and navigating uncertainty, making it a necessary skill for engineers. There is a drive to include more agentic opportunities in engineering curricula, particularly in the early years of the undergraduate program. This work comes from a larger study motivated by supporting instructors in designing agentic opportunities in first-year engineering curriculum.

To be able to design effective agentic opportunities, we must first understand student experiences with such learning environments. Thus, the specific research questions addressed in this paper are: *How do students perceive agency in open-ended modeling problems (OEMPs)? What are the outcomes of responding with agency in such problems?* We answer these questions using a thematic analysis of 16 semi-structured interviews with students from multiple cohorts of a mechanics course sequence. Multiple OEMPs were designed and implemented to give students experience with making assumptions, assess constraints, and conduct analysis to meet specific requirements. Retrospective interviews were conducted with students to understand their problem-solving process, compare these problems with other assignments within and outside of the course sequence, and describe their affect during such problem-solving. Students were also asked to share their opinions on OEMPs as favorable learning opportunities.

An open-coding approach was used to generate codes interpreting the student experiences in the context of problem-solving agency. We analyzed student responses in the interviews to first find instances where these problems were perceived as agentic opportunities. Students described these problems as having more "freedom" compared to the traditional "book problems," particularly in the selection from multiple approaches to solving them and having "choices" at various stages of the problem. To answer the second research question, we present several themes of outcomes of such agency namely learning, retention, skill development, and metacognition. Implications for first-year instructors are drawn to outline the benefits of implementing such problems in early engineering education.

Introduction

Professional engineers solve real-world problems that are ill-defined and require them to grapple with constraints, uncertainty, and decision-making complexities. Engineering design and open-ended problem-solving calls for getting accustomed to the associated discomfort in prioritizing certain constraints and stakeholder needs over others, selecting a design idea, and making decisions about different aspects of the design [1]. One way to operationalize the practice of such skills is under the theoretical construct of agency. Broadly speaking, agency is described as the capacity of an individual to exercise control and take action towards a goal [2]. So, when an engineer enacts agency with the goal of solving a problem, they are utilizing their freedom to make decisions or take actions in the form of making tradeoffs between constraints and satisfying requirements, bounding the problem, and selecting and iterating over multiple

problem-solving approaches. Thus being adept at practicing agency is a highly valued employable skill [3].

While engineering curricula has historically relied on traditional problems that are well-structured, constrained, and have convergent solutions [4], [5], [6], courses like capstone design provide students with opportunities in open-ended problem solving. Research has suggested that even at upperclassmen years of engineering degree programs, students struggle with problem-definition, making assumptions, selecting the approach to the solution, connecting multiple components cohesively, and being comfortable with ambiguities [6], [7], [8]. In response, there is a drive to reform fundamental engineering courses into providing more "authentic" and "workplace-like" experiences at a much earlier stage [5], [9], [10], such as first-year engineering courses where students come in with very little exposure to open-endedness [11], and thus lack comfort in practicing agency.

This study is an important step in contributing to this reform effort, where understanding student experiences with agency can help inform the design and appropriate scaffolding of open-ended problems. While previous work has focused on preliminary analyses to explore broad themes of student experiences with agentic opportunities [12], in this paper, we provide a deeper insight into agency in open-ended modelling problems. Specifically, the research questions addressed in this paper are: *How do students perceive agency in open-ended modeling problems (OEMPs)? What are the outcomes of responding with agency in such problems?* Thus, we look for evidence of agency when students discuss the nature of these problems and then describe their perceptions on the result of these experiences. The larger study is focused on grounding these perceptions in theory and evaluating the outcomes of such experiences using other objective frameworks.

Literature review

While agency has been studied heavily in the social sciences [2], [13], engineering education research has a limited discussion on the antecedents and consequences of agentic experiences. Social cognitive theory defines agency as a domain-specific concept [2], which means the contexts can govern the scope of agency. To elaborate, while scholars have discussed the implications of broader *learner agency* [14] and *epistemic agency* [15], a group of engineering education scholars have investigated the scope of the decision-making ability to define and bound a design problem specifically as *framing agency* [16], [17], [18]. Other research conceptualizes agency as a multidimensional construct with factors at the intrapersonal, behavioral, and environmental levels such that the same agentic experience can be perceived differently owing to differences in predispositions and attitudes of individuals, or the instructional and organizational contexts of those experiences [3], [19]. Some factors that have been found to influence agency in engineering learning contexts are student motivation, self-efficacy, trust for teacher, and teacher support [19], [20]. However, it is unclear how students value the importance of agentic learning opportunities. There is also hesitance in adopting open-ended problems because instructors fear the student resistance to discomfort experienced with the ambiguity in such problem-solving [21]. Thus, a deeper understanding of student perceptions can help support the implementation of such experiences, particularly in earlier courses. To support addressing this gap, we operationalize agency as applicable in the scope of the freedom experienced and enacted during open-ended problem solving.

Methods

Building on prior work [12], this paper involves a thematic analysis of 16 semi-structured interviews with students from multiple cohorts of a two-part mechanics course sequence (statics and dynamics). Seven came from students in the statics course as part of the first cohort and 4 in the dynamics course; from the second cohort, 2 were from the statics course and 3 from the dynamics course. Two students were interviewed both in statics and dynamics courses, so the total number of students was 14. This first-year course sequence was offered at a small private institution in southern United States where data was collected to understand students' problem-solving approaches and how engineering judgement develops with such experiences. Multiple OEMPs were designed and implemented to give students experience with making assumptions, assess constraints, and conduct analysis to meet specific requirements. Retrospective interviews were conducted with students to understand their problem-solving process, compare these problems with other assignments within and outside of the course sequence, and describe their affect during such problem-solving. Students were also asked to share their views on OEMPs as favorable learning opportunities. An open-coding approach was used to generate codes interpreting the student experiences in the context of problem-solving agency. After the first author generated the initial codes, we iterated over these codes through discussions and reconciliations with the second author. This helped us in establishing the quality of our methods.

Description of OEMPs

Multiple open-ended problems were assigned through the course sequence requiring students to make assumptions, create free-body diagrams, and conduct an analysis of the system to meet specific requirements under clear constraints. The statics course required the design of an element in a replacement of traditional crutches that could perform as a hands-free mobility device. In dynamics, the first OEMP was based on analysis of a two-body system involving a car crash. The second OEMP allowed students to self-select a system and provide design analyses. The instructor provided a descriptive problem statement with resources such as product manuals and crash investigation reports. The assignments involved both individual and team-work. The instructor observations and student feedback led to minor revisions to the problems between the two cohorts. More details about the OEMPs are available in prior work related to this study [22].

Findings

In this section we outline the themes generated from our coding process. The findings are organized by the research questions and student quotes from the interviews are included to elaborate on the themes. All names used are participant-selected pseudonyms. As mentioned earlier, Lane and Cristina were interviewed for both courses, and so their quotes are clarified with the course associated with them.

RQ1: Perceptions of agency

The first research question guiding this study is: *How do students perceive agency in open-ended modeling problems (OEMPs)?* We analyzed student responses in the interviews to first find instances where these problems were perceived as agentic opportunities. Participants were asked to compare the OEMPs against other assignments in the mechanics courses and in other courses they had taken. Several participants referred to other assignments as "book-problems" and the OEMPs as "real-world" problems. For example,

> **Lane in Dynamics:** *I mean, apart from design, of all my other engineering classes are very book problem-based based and you apply what you're learning to the problem. And so, you don't really have to flounder for which concept to use at that point, because you know this is what we're doing. This is how you apply it. So, this project was definitely the biggest difference... Because I believe like these open-ended problems really help you learn what the engine... Just in a general engineering process is and how you develop ideas, and you test them, and you fix them and everything. And the open-ended problems are a lot more like problems that you'd encounter when you graduate....*
>
> **Joe Wong:** *We have a lot more freedom when we're solving this problem. And I think that is pretty large because that would be the closest to the real world is no one's going to tell you,*

On similar lines, participants mentioned how other problems are more structured.

> **Joe Wong**: *And in the homework problem, all the variables we need are defined. So, we didn't have to research, which we get a lot of in these two scenarios.*

In several cases, participants observed the "freedom" they had in several aspects of the problem-solving process. Firstly, the student-selected system in the final project in Dynamics allowed them to define the problem themselves:

> **007:** *It was very open ended, like we got to pick literally anything so thinking about that was interesting.*
>
> **Lane:** *But what [was] really different in this project was the fact that you came up with your own system. You came up with how it functioned and so, it was even more broad and even more open-ended than any design project I've ever had. Because you're always given a basis for something, for where to start. So, it was definitely really interesting to be given no direction. Like do whatever you want. Find a system... The only direction we had was you had to have this number of rigid bodies, but that freedom was nothing I had ever been given in any other engineering class.*

Secondly, in the selection of their approach to problem solving:

> **Dylan:** *It was so open ended. And there was so many ways to take it... Well, there was no technique we were told we had to use and there was no limits or constraints and so I actually instead of just going through the homework and saying, "I know how to do this" and then sitting down and doing it, I actually had to sit down and look at it and plan out what I was gonna do before actually doing it.*

In some specific cases, students described how the instructor further encouraged them to take ownership of their work by making intentional choices

> **007:** *She [the professor] did suggest like this is going to be a decision that you have to make, and it'll be interesting to see. And she kept talking about it [model selection] both ways. So, we wanted to kind of show both a little bit.*

These excerpts provide a picture of how students experienced the OEMPs. We observe that students perceived the problems gave them opportunities to practice the freedom of making

choices and action-oriented decisions towards the intentional goal of solving a problem. This is in line with our operational definition of agency.

RQ2: Outcomes of agency

The second research question guiding this study was: *What are the outcomes of responding with agency in such problems?* We identified several codes that related to the consequences of engaging in opportunities of agency as perceived by the students. These codes related to different instances of how students perceived the open-ended problems affected them.

Learning and retention

Students expressed how engaging with the open-ended problems really helped them learn the course content better. Moreover, they also believed that they are likely to retain the course topics for a longer period of time because of the manner they applied these concepts to open-ended problem statements. They pointed out how the problems were very "application-oriented" in that they helped them learn how to evaluate which specific course topics apply to the problem at hand and also the appropriate ways to apply them. Further, the iterative nature of the problem-solving process helped them learn more even when it came at a cost of more time and effort.

> **Larry Nguyen:** *I think I am going to remember how to do equilibrium equations or how to balance out a moment, for a really long time because I did this open-ended model project. Yeah, because I looked at how to do everything so much, it's just embedded in my brain now.*

Professional skills

We identified instances where students voiced developing professional skills outside of course content. They attributed learning these skills because of the nature of open-ended problems and also because of how the OEMPs were structured and implemented in the classroom setting. Students had worked on problems both individually and in teams at different points in the semester. Skills such as critical thinking, creativity, and leadership were mentioned. While some students noted feeling more confident in general at the end of the experience, some expressed how the problems helped them learn the value of teamwork and being organized in a team. A noteworthy quote from Lane in dynamics demonstrates how learning to seek help also emerged from these experiences.

> **Lane in Dynamics:** *... but I felt like using Dr. [instructor name] as a resource became a lot more important. And honestly, that was a skill for me to learn. Being able to go and ask for help and have her, not telling me the answer, but, say, "This doesn't make a whole lot of sense, try approaching it in another way."*

Engineering Judgement

We also identified engineering judgement [23], [24], [25] as a consequence of agency. In this context, students expressed engaging with OEMPs helped them develop engineering judgement, evident in their use of phrases such as "I learned that this makes more sense", or "understood that this is more reasonable."

> **Lane in Statics:** *So, my assumptions for just kind of...became more and more educated as I learned more about the, um, the tools we had to use, the moments, internal forces and things like that.*

Engineering identity

An important finding in our analysis of agency outcomes was the contribution of the experience to their growth as engineers. This code is specific to how they learned how to identify as an engineer or came to understand what being an engineer meant to them.

> **Joe Wong:** *I personally think that this helps me develop as an engineer because this is much more like you said before, in the real world, we won't just have a textbook and we have a table to look at real answers at the end there. So, we have to come up with... If we're like a pretty senior engineer, then we have to kind of come up with how to solve a problem. And this really helps with our problem-solving skills.*
>
> ***Cristina in Dynamics:*** *Compared to all the other classes and all the other problems and everything, it's the most engineering thing we've done so far.*
>
> ***Joe Wong:*** *We're not only solving a problem, but we are like kind of seeing our role in a group a lot and I think in a real-world sense because it felt like we were all engineers working on a project and then it kind of gave me a sense of where I want to be in terms in a group. I think that was really interesting for me to see at least firsthand.*

In instances where students expressed these experiences to be that of an engineer, they also compared them to professional scenarios in how the open-ended problems came close to their perceptions of the “real-world” problems.

> **007:** *I think the, these, these would show up in an ideal engineering course because in the real world, whatever that looks like, solving engineering problems is open ended.*

Metacognition

In a few interviews, student perceptions of how the OEMPs helped them pointed to them learning about themselves and provoking thoughts that helped them understand how they learned. The following descriptive quote from Lane is an exemplar of this finding.

> **Lane in Dynamics:** *But just more general, did all of the open-ended problems kind of helped me learn how I think? It helped me learn how I start a problem, what I usually get stuck on. And then I learned that I like the whole research aspect of it. I always do a lot more than necessary because I like having each of those values. And so, it helped me learn how I think about these problems. And it helped me learn how I work through them. I get frustrated, but if I do this, if I walk away, if I come back. But if I do this, if I walk away, if I come back, if I just start the problem completely over, which I did multiple times, and I just try a different attempt or a different method, even though it might not lead somewhere, putting all of those attempts together will get me to my final idea like, "Okay, now I understand how to do it." And so, I did that for every open-ended problem in both Mechanics 1 and Mechanics 2. And just helped me learn more about my process in addition to the concepts... o, yeah. I mean, in addition... Yeah, just in addition to the concepts because they all definitely helped solidify mechanics concepts in applications, but you learn more about how you learn and how you work through problems as well.*

While these findings describe a more positive overview of the outcomes of OEMPs as agentic opportunity, we want to note that students also expressed challenges in the process of such problem-solving including "frustration" and "feeling overwhelmed" with the initial ambiguity of the problem statement, the lack of clarity in needing to make assumptions, the demand for more time as a result of the iterative nature of problem-solving, and a pronounced discomfort in the absence of a single "right answer" for students who struggle with decision-making or facing choices. These same students also expressed diminishing negative affect in the later OEMPs as they got used to the uncertainty with exposure to the knowledge of the process of solving an open-ended problem.

Prevalence of codes

As a preliminary comparative analysis, we tried to see how these codes were prevalent across our data. Table 1 shows the number of interviews each code appeared on. This preliminary analysis signifies that our codes were relatively prevalent across our sample and will help us in cross-case comparisons for a deeper analysis of how these experiences are similar or unique between students.

Table 1: Prevalence of codes in interview transcripts

Codes	**Interviews with mention of the code**
Perception of agency	13
Outcome: Learning and retention	12
Outcome: Professional skills	7
Outcome: Engineering Judgement	10
Outcome: Engineering Identity	6
Outcome: Metacognition	3

Discussion

Our findings for RQ1 above help us understand the different ways students experienced freedom in OEMPs and thus show evidence of OEMPs providing exposure to agency in problem-solving. In a related but different study [26], we discussed the different types of agency students enacted in design problems. We draw similarities in the findings of these studies and extend the multidimensional nature of agency. In particular, the same open-ended problem in both studies were viewed differently by different participants, sometimes owing to their own comfort with navigating ambiguity, and sometimes shaped by the structure of the team dynamics in the course. This is noteworthy in designing open-ended problems as instructors may need to consider factors at different levels that may influence the impact of the learning experience – including learner characteristics in the courses and the broader contexts such as course format that may enable or constrain learner agency. The latter is of particular interest in the current age of generative AI

tools where student reliance on LLMs can often negatively impact their learning and retention of course content. While the OEMPs in the current study were supported with resources such as manuals and crash reports, students expressed using external resources to information to make assumptions [27]. The constraints placed on these external resources can help promote or limit the "authentic" nature of these learning problems.

For RQ2, we identified several different levels of influence agency had on student's educational and professional growth including skill development, engineering identity and metacognition. Of particular note, in the context of our larger study, is the student discussion of engineering judgement. In yet another study, we investigated the ways students responded to the agency in OEMPs [27]. One of the ways students enacted agency was by relying on their engineering judgement to make choices in assumptions and approaches in problem-solving. The expressions of engineering judgment in the context of findings for RQ2 are different because they refer to how the experience of OEMPs caused them to better understand what choices or assumptions are appropriate to make. This shows a complex cyclic nature of agency where in the process of enacting agency, students further improved their skills needed for agency. This cyclic nature also contributes to evidence in favor of implementing agentic opportunities, despite the challenges and initial discomfort associated with such learning experiences. Our findings supported the improved learning and increasing comfort in grappling with the uncertainty inherent in problem-solving agency. Prior work based on these OEMPs include a discussion of instructor reflections on scaffolding for such problems [22], [24], [25], [28].

Conclusion

In this study we outlined the potential of open-ended modelling problems as favorable agentic opportunities in the context of first-year engineering courses. Our findings suggest that students perceive a positive impact of such experiences in their learning and professional development while also learning to navigate the challenges associated with such experiences. We draw out the complex multidimensional nature of agency in such contexts and conclude by recommending that scaffolding strategies in open-ended problems involve considerations of both learner characteristics and the impact of the environment on the learning experience. Parallel work from this data involve exploring how students take actions or grapple with challenges during OEMPs as agentic opportunities. Future work will involve a deeper analysis of the student experiences to understand how these OEMPs were perceived similarly or differently across individuals. Our work on agency in engineering problem is ongoing and will involve investigations such as the impact of AI on learning in agentic opportunities and a comprehensive comparison of student perception of agency outcomes with more objective measures using frameworks like transformative learning.

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