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PAPER

Growing the Entrepreneurial Mindset in First Year Engineering Students Using Sociotechnical Design Challenges

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ABSTRACT

Engineering graduates must acquire both technical knowledge and a diverse range of professional skills to effectively address the current global challenges. Equally important is a profound understanding of how technological solutions are influenced by the human and natural environments in which they are implemented. An open-ended, team-based design challenge integrates entrepreneurial-minded (EM) skill development into an interdisciplinary first-year engineering course that approaches engineering from a sociotechnical perspective. A mixed-methods study using a post-course reflective questionnaire explored students' self-perceived development of EM skills. Quantitative results from a series of 5-point Likert-type questions indicate that students felt they developed EM skills in all three areas of the 3-C framework, with average mean scores above 4.0 in all three categories. Scores were significantly higher in the Connections and Create Value subscales (mean 4.31 ± 0.62 and 4.23 ± 0.76, respectively) compared to the Curiosity subscale (mean 4.04 ± 0.84). Student comments on open response questions support the overall value of the project and the broader sociotechnical learning outcomes that were achieved. Overall, this study suggests the effectiveness of incorporating open-ended, sociotechnical engineering design challenges to develop skills that will better prepare students for collaborative work on complex, interdisciplinary problems they may encounter in their professional careers.

KEYWORDS

first year engineering education, sociotechnical, engineering design, entrepreneurial-minded (EM) learning

1 INTRODUCTION

More than ever, the current engineering graduates must be prepared to tackle complex, interdisciplinary problems that have far-reaching societal consequences. Wicked problems [1] related to sustainability, climate change, and the

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approaching 'fourth industrial revolution' (e.g., automation, artificial intelligence (AI), advanced materials, bio, nano, and neuro-technologies [2]) will require innovative, entrepreneurial leaders [3] who possess a solid understanding of technological concepts as well as a range of professional or 21st century skills, including communication, creativity, teamwork, and leadership skills [4–6]. Equally or perhaps even more important is a profound understanding of the sociotechnical nature of engineering and technology, recognizing the extent to which technological solutions are embedded within the framework of human and natural environments [3] [5] [7].

Engineering students often begin their university studies with a preconceived notion that their work will focus on the WHAT (what technology will we develop?) instead of the WHY (what problem are we solving? for whom?) [6]. Recent evidence indicates a decline in students' awareness of social responsibility and the societal impacts of technology throughout their engineering education [8] [9]. Indeed, despite decades-old reports from the National Academy of Engineering (NAE), the National Science Foundation (NSF), and the American Society for Engineering Education (ASEE) calling for a broadening of engineering education [4] [10] [11], engineering education and the engineering culture in general still tend to overemphasize the value of technical achievement compared to the social, cultural, or political implications of the engineer's work [9, 12–14]. Technical expertise is important, but it will not sufficiently prepare graduates to solve the complex global challenges they will face as professionals. Increasing employability remains a concern for higher education institutions and often requires more clarity in the areas of student skill development. In line with this need, engineering education must adequately prepare students with the skills they need to tackle these complex challenges and be better equipped for the workforce [15–19]. This calls for an early emphasis on developing broad professional skills and providing authentic teaching and learning opportunities that demonstrate contextualized engineering problem-solving early in the curriculum [20]. Delaying the introduction of engaging, context-oriented engineering design until the second or third year may discourage students from persisting in their majors because they may fail to see the relevance of what they are learning. Students need to learn early on that the engineering problems they will face will be tightly intertwined with societal, humanitarian, economic, and political contexts. Innovative solutions must genuinely meet stakeholder requirements.

Learning outcomes established by the Accreditation Board for Engineering and Technology, Inc. (ABET) and echoed by the International Engineering Alliance's (IEA) Washington Accord provide a framework for considering a range of criteria that extend beyond technical content knowledge. These outcomes require students to develop broader professional skills, including teamwork and communication skills, complex problem-solving requiring critical thinking and high-level reasoning, and an accurate understanding of stakeholders' perspectives in the design of systems [21] [22]. Although the outcomes are valuable drivers for change, neither ABET nor the IEA offer curricular or pedagogical approaches to achieve them.

Many of these broader professional skills can be developed among students by challenging them with open-ended, real-world design problems. A growing trend in engineering design courses is to utilize a "design thinking" framework, which approaches design more broadly as a thoughtful process that requires the development and evaluation of multiple solutions [23–25]. This framework offers a solid foundation for developing critical thinking skills. However, the emphasis on non-technical applications, such as Stanford IDEO's Wallet Project or Backpack Re-design [25], often poses challenges for engineering faculty when it comes to adapting the curriculum to technical topics. Moreover, design is typically taught in the sophomore and senior years, culminating in a capstone design project. Introductory first-year courses have been developed to bridge the gap between students' perceptions and expectations of engineering and engineering curricula, as well as to dispel many of the generalizations students may have at the beginning of their engineering degree [26] [27], yet these courses often have to balance content with other general first-year orientation topics. Cornerstone design, taught in the first year, is less common and tends to focus on developing technical problem-solving and other "hard skills" such as computer drafting, programming, etc. [28] [29].

Even broader than design thinking is approaching engineering from a sociotechnical framework. This technique exposes students to engineering in a contextual manner and emphasizes the significance of incorporating social dimensions throughout the design process [30] [31]. For example, Acumen Academy provides numerous free online courses, workshops, and seminars that specifically emphasize the sociotechnical aspects of engineering. However, it is challenging to recreate these experiences in traditional classroom settings. At the other end of the spectrum, holistic curricular models integrate coursework across disciplines to reinforce students' broad sociotechnical perspectives. An example of this is the product design and innovation (PDI) program at Rensselaer Polytechnic Institute [32]. These approaches are typically introduced in mid- to upper-level engineering courses where design is more prevalent [30] [33]. There is some evidence of first-year engineering courses that present engineering within a societal context. However, most of these courses rely on case studies, conceptual designs [5] [34], or online or virtual programming [35]. The integration of hands-on projects is limited [36].

The educational intervention described in this research integrated entrepreneurial-minded (EM) skill development into an interdisciplinary first-year engineering course that approaches engineering from a sociotechnical perspective. Entrepreneurial-minded learning (EML) provides students with learning opportunities that challenge them with real-world, open-ended problems. This approach encourages students to seek creative, value-added solutions that are tailored to the needs of stakeholders. EML outcomes align to a great extent with broad professional skills [37]. In this research, an open-ended team design challenge exposed students to a range of engineering-related topics in a small, interactive class structure, with a strong emphasis on framing solutions within a societal context. The design challenge required students to progress through the design cycle throughout the semester, ultimately resulting in the development of a functional prototype that meets predetermined performance specifications. The project was designed to engage students in self-directed learning that helps them "learn to learn" and incorporated many aspects intended to develop students' entrepreneurial mindsets. These aspects include understanding the bigger picture, recognizing opportunities, evaluating markets, and learning from mistakes to create value for themselves and others [38]. Our design project emphasized creating value by placing a strong emphasis on understanding and clarifying the problem that needs to be solved and focused on creating solutions that address critical customer needs or local or global problems. These were considered the first and most important step in the engineering design process and the ultimate goal of engineering design, respectively. Students were driven by their own curiosity to explore multiple perspectives and understand the broader world. They also sought to make connections as they looked for new ideas and approaches to the design of their prototype. Additionally, they were challenged to work together effectively as a team to accomplish their tasks. What makes our project particularly unique is the emphasis placed on simultaneously approaching engineering design from a sociotechnical frame of reference.

This paper describes a study that examines the influence of an open-ended design challenge on a specific group of students who took part in the course during their first semester in an engineering curriculum. We investigate students' perceptions of engineering as a sociotechnical endeavor, with a particular focus on their skill development within the KEEN 3C's framework. The study is guided by the following research question:

- How does designing from a sociotechnical lens impact students' EM skill sets?

2 BACKGROUND AND CONCEPTUAL FRAMEWORKS

This pedagogical work is based on two conceptual frameworks: EML and sociotechnical engineering design. We will describe each framework in the following sections. The design challenge presented and assessed here is grounded in the intersection of these two frameworks. This overlap is described more specifically in "EML from a sociotechnical lens".

2.1 Entrepreneurial mindset and entrepreneurially minded learning

In the context of engineering, entrepreneurship extends beyond the development of startups and business opportunities. An Entrepreneurial Mindset is broadly defined as the way entrepreneurs think differently about given tasks [39]. Bekki, et al. [12] emphasize "the set of cognitive behaviors or skills that orient an engineer towards opportunity recognition and value creation." The Kern Foundation [38] has developed a "3C" framework that organizes EM skills into three broad student learning outcomes:

- Exhibit curiosity by exploring technology trends and considering multiple perspectives in a rapidly changing world; self-growth through independent, self-directed learning.
- Establish connections by thinking "outside the box," combining information from various resources, including knowledge gained from peer-to-peer learning, to gain insights and connect knowledge to real-world applications.
- Identify solutions that create value by understanding and meeting customer needs, promoting ethical best practices, and having a positive impact on society. Additionally, persist through and learn from failure.

Entrepreneurially-minded learning provides students with opportunities to approach problems and challenges in a more entrepreneurial way. This is achieved through authentic instruction that emulates real-life application of knowledge, specifically fostering three key learning outcomes known as the 3-C's. Such instruction develops students' technical knowledge and skills, as well as their curiosity, their ability to identify problems, and their ability to integrate knowledge from various sources to develop solutions that create value [37] [40] [41].

EML outcomes align with the push for education to develop students' "T-shaped" skills: deep technical knowledge as well as a range of broad professional and cross-disciplinary skills, including intercultural competencies, entrepreneurship, and mindsets that support ethical and sustainable practices [42]. Several of these competencies are also supported by ABET learning outcomes, such as the ability to "analyze the social context in both historical and contemporary settings," "communicate effectively," "engage effectively in diverse teams," "reflect and act ethically," and "design in context" [21]. Introducing entrepreneurship within engineering curricula or through co-curricular programs is an effective strategy for meeting these competencies [43]. Bekki et al. [12] maintain that EML should be embedded throughout the undergraduate curriculum, placing it on par with efforts to "make engineering more hands-on and increase diversity". Indeed, EML integrates many teaching strategies that are widely recognized for developing students' professional skills, such as open-ended problem-solving, teamwork, and communication skills [3] [4].

Entrepreneurial-mindedness is also promoted with other evidence-based, student-centered teaching and learning strategies, such as design-based, collaborative, and project-or problem-based learning. These strategies are widely known to improve student engagement and learning [12, 44–47], develop professional competencies [48], and engage and retain a broader range of students [26] [27] [49]. EML has been provided to engineering students through online training modules [50], multi-course series [51] [52], and holistic curricular revisions and co-curricular activities [53–55]. Efforts to integrate EM projects and design modules within existing engineering courses are also gaining traction, but most of these efforts are focused on middle- and upper-level classes [40, 50–52, 56–58]. Few programs explicitly integrate EML into the curriculum in the first year, although the numbers are growing [41] [59] [60]. Assessment efforts have shown that EM activities are successful in exposing students to EML, enhancing their awareness of EML concepts, and developing their EM skills. Additionally, these activities have been found to improve intrinsic motivation and self-efficacy.

2.2 Sociotechnical engineering design

Coursework that contextualizes engineering within a sociocultural and economic framework helps students understand the social implications of engineering and exposes them to sociotechnical problem-solving [31] [61]. The National Academy of Engineering emphasized in 2005 the importance of engineering graduates "recognizing the broader contexts that are intertwined in technology and its application in society" [4]. In response, several curricular and extracurricular initiatives have been implemented to enhance the preparedness of engineering students in understand the global implications (societal and environmental) of engineered solutions and engineering design [5] [20] [30]. Some of these initiatives are integrated into first-year engineering courses [34] [62]. Specific to this research, the course "Engineering and Society," described in more detail in [62], is a first-year engineering course taught by the first author. It approaches engineering from a sociocultural perspective. The course has been shown in previous research to positively influence students' appreciation of engineering as a broad, creative discipline that is a sociotechnical endeavor [62] [63].

Design projects are recognized as a prime opportunity to incorporate these outcomes into the undergraduate curriculum [33]. Kilgore et al. [5] support the importance of introducing students to engineering in a contextual manner during their first year. This can be achieved through cornerstone design projects that offer a glimpse into the practical aspects of engineering [35] [64] [65]. These projects also emphasize teamwork, communication, and hands-on learning, which are appealing to a diverse range of students and contribute positively to their engineering identity [66]. There is significant overlap between EM and the engineering design process [67]. Incorporating engineering design in the first year gives students early exposure to the importance of developing user-centered engineering solutions that address diverse societal needs and consider the implementation context [5]. User-centered innovation is reflected in design thinking, whose primary tenet is the need to understand or empathize with those who might benefit from an innovation [68] [69]. Walther et al. [61] and Kouprie and Visser [69] have argued for including empathy as a core skill in engineering and design. Indeed, empathy and design thinking are both key competencies of the create value outcome of EML, enabling the development of technological solutions that are effectively integrated with community dynamics and aligned with people's needs [54] [70].

Raising students' awareness of the social dimension of engineering and the role engineers play in helping people can also enhance student engagement and retention [14, 71]. In particular, women and students from other underrepresented minority groups, who have been shown to leave in disproportionate numbers following the first-year prerequisite engineering courses [72], have demonstrated a greater sensitivity to the broader societal context of engineering design. This is evident in their recognition of the clear relevance of engineering to improving society or enhancing the quality of life [5] [31] [73] [74]. Women are generally drawn to careers that involve working with and helping people and communities [75] [76]. Yet, a study by Besterfield-Sacre et al. [77] found that among first-year engineering students, females had a lower perception than men of "how engineers contribute to society". Other studies have shown that female engineering students are more likely to discuss and recognize the significance of societal context in engineering design compared to their male counterparts [5] [78]. Likewise, Kilgore et al. [5] found that first-year students tended to approach problem-solving and design more broadly, focusing on the context rather than the details. Thus, in addition to exposing students to positive societal impacts, contextualizing engineering design by approaching it through a sociotechnical framework can better engage first-year students in general, and especially those from underrepresented minority groups, in engineering studies.

2.3 EML from a sociotechnical lens

Providing students with opportunities to engage in interdisciplinary problem-solving and design that fosters EM skill development while simultaneously emphasizing the sociotechnical systems in which the design solutions will be situated will help prepare them for a workforce where they will be required to tackle complex, wicked global problems in a rapidly evolving profession. Examples in the literature of programs that integrate EM skills while incorporating a sociotechnical perspective are limited but significant. These examples vary from individual courses to comprehensive institutional initiatives. Many of these efforts have demonstrated positive impacts on students, including their ability to think with an entrepreneurial mindset, improved awareness of multiple problem solutions, and a greater inclination to use a social lens when dealing with complex problems [79] [80]. Yet these efforts are, for the most part, implemented in middle- and upper-level engineering courses.

Two reports by Graham [81] and Hadgraft and Kolmos [3] cite examples of innovative programs that achieve this integration through university-wide initiatives in the UK, Singapore, Australia, and the Netherlands. The Charles Sturt University Model [82] offers a 5.5-year joint bachelor/master program in civil systems engineering. This program combines online coursework with project- and work-based education. In the U.S., the 'Iron Range Engineering Program' [83] offers a two-year PBL curriculum to community college graduates. This program involves students solving real, entrepreneurial-based problems. Student graduates rank highly in both content knowledge and professional skill development.

In contrast to these institutional reform efforts and with a greater emphasis on the societal context, Bertoni [79] utilized challenge-based learning (CBL) to introduce Danish mechanical engineering students to design thinking and enhance their EM skills through collaboration with socially oriented companies. Their approach utilized large, real-world, open-ended problems to concurrently cultivate students' teamwork, communication, and leadership abilities, their entrepreneurial mindset, and their capacity to tackle societal issues through engineering problem-solving. An analysis of seven projects conducted over two years indicates that students developed EM skills. Moreover, students who worked with socially-oriented companies interacted with a larger number of stakeholders and gave greater consideration to the value their solutions would provide compared to their counterparts who worked with traditional companies. They also demonstrated a greater tendency to use a 'social lens' to determine the overall value of a proposed solution. Student reflections expose how the experience enhanced students' ability to tackle complex problems, acknowledging that each situation is distinct and necessitates well-thought-out solutions. Students who worked with socially-oriented companies were more aware that there are often multiple solutions to complex problems, many of which are not mutually compatible, and that these solutions are often temporary in nature.

Researchers in the Integrated Engineering Department at the University of San Diego have situated EM more directly within an interdisciplinary course. This course emphasizes the development of technological solutions that have a positive impact on society [80] [84]. The project-based course challenges interdisciplinary teams of students from the Schools of Engineering and Peace Studies to solve a real-world design problem. Course assessment revealed that student and team heterogeneity was a factor in helping students develop an entrepreneurial mindset by forcing them to confront and negotiate issues from different perspectives [80].

Aside from these examples, the review by Hadgraft and Kolmos [3] describes a variety of emerging teaching and learning strategies that highlight societal context and human values. These strategies aim to better equip students with interdisciplinary skills to develop effective and sustainable technological solutions. Their review exposed four distinct approaches that are typically incorporated individually into discrete courses. They propose that these approaches should be integrated into complex projects in order to develop students' technical competencies and professional skills such as communication, teamwork, ethics, design thinking, and systems thinking. Three strategies they describe overlap with the approach taken in this research: student-centered learning, which is similar to EML in that it includes collaborative, team-based learning, design-based learning, and project-based learning; contextual learning (integration of practice); and professional competencies. Although Hadgraft and Kolmos [3] cite examples of university- or department-wide integrated curriculum models, the spirit and intent of their argument align with the motivation behind this research, and their recommendations are evident in our open-ended design challenge.

3 METHODS

3.1 Study design

This study utilized a quasi-experimental design with convenience sampling and reflective (post-only) data collection, lacking a control group. We employed a mixed-methods approach, which involved the integration of Likert-type survey data with free-form responses to a series of open-ended questions. The study was conducted as part of a larger ongoing research project involving first-year engineering students at the university. This project was approved by the university's Institutional Review Board as an Exempt Category 1 study. The following sections describe the study participants, educational intervention, data collection, and analysis procedures that support the study design.

3.2 First-year course and participation information

The study participants were first-year engineering students from Fall 2021 (F2021). They were enrolled in two equivalent sections for an introductory engineering course that was taught by the first author. The course, "Engineering and Society," addresses various topics in different contexts. These include the history of engineering and the intricate relationship between engineering and society, engineering ethics, and extensive coverage of engineering design, which encompasses teamwork and communication. With a focus on science, technology, and society (STS) and a significant amount of time dedicated to engineering design, many of the course outcomes are in line with both the KEEN 3-C framework for EM learning and ABET's criterion 3 program outcomes [21, 38].

The sample of participants consisted of 48 students, with the majority being white (86%) and male (85%). These characteristics generally reflect the breakdown of the School of Engineering: 22% female, 78% male, and 19% non-white. All engineering majors were represented, including chemical, civil, environmental, electrical, mechanical, and aerospace.

3.3 The open-ended design challenge, an EML activity

This research centers around a semester-long, team-based design challenge that requires students to apply the engineering design process in order to solve a problem that is relevant to society. The F2021 student cohort was tasked with designing and constructing a working prototype of a trans-radial prosthetic arm for children. After an in-class team-building activity that introduced students to the iterative and open-ended aspects of design, as well as the stepwise design cycle approach, the students were then assigned a team design challenge. Project elements, as shown in Table 1, are aligned with the 3C pillars of the KEEN framework and correspond to the overall progression of the engineering design cycle. The timing shown in Table 1 is approximate and varies according to other class activities that are happening simultaneously with the design project. In general, the project requires student teams to work independently towards their goal of constructing and demonstrating a prototype. There will be occasional class time to guide students through different stages and to check their progress. Design challenge assignments are available upon request from the author; Figure 1 shows a sample of finished prototype designs.

Table 1. Curricular elements for the design challenge, mapped with KEEN 3C framework

KEEN Framework	Project Element	Week	Description
Connections	Team Formation	1–2	Teams are assigned using CATME Team-Maker [85]. Assigned teams participate in team-building activities, assign roles, and create team contracts.
Curiosity, Create Value	Background Research	2–3	Students conduct research to better understand the customer, their needs, and the societal context in which their design will be used. Students explore historical and recent technological developments relevant to the technology.
Curiosity, Connections	Brainstorm	3	Idea-triggered brainstorming session [86], guided by the instructor, ensures that all students' voices are heard. The process is followed up with an informal, cyclical brainstorming session.
Connections, Create Value	Project Proposal	5	Written report that (1) justifies the relevance of their design project; (2) proposes an initial design, with sketches and draft budget; and (3) outlines the team's timeline and approach to complete the challenge.
Curiosity, Connections, Create Value	Build and Test	6–11	The iterative hands-on work of acquiring materials, constructing the prototype and testing its performance. Continues, to varying degrees of sophistication, through to the end of the project.
Connections	Progress Report	9	Professional written report to (1) inform the customer about the status of the project and the timeline for completion; (2) provide updated budget and updated (sometimes finalized) drawings.
Curiosity, Connections, Create Value	Prototype Demonstration, Presentation	12	Professional team presentations are used to describe their experiences progressing through the design cycle and reaching their endpoint. They also demonstrate that their prototype meets all performance specifications.

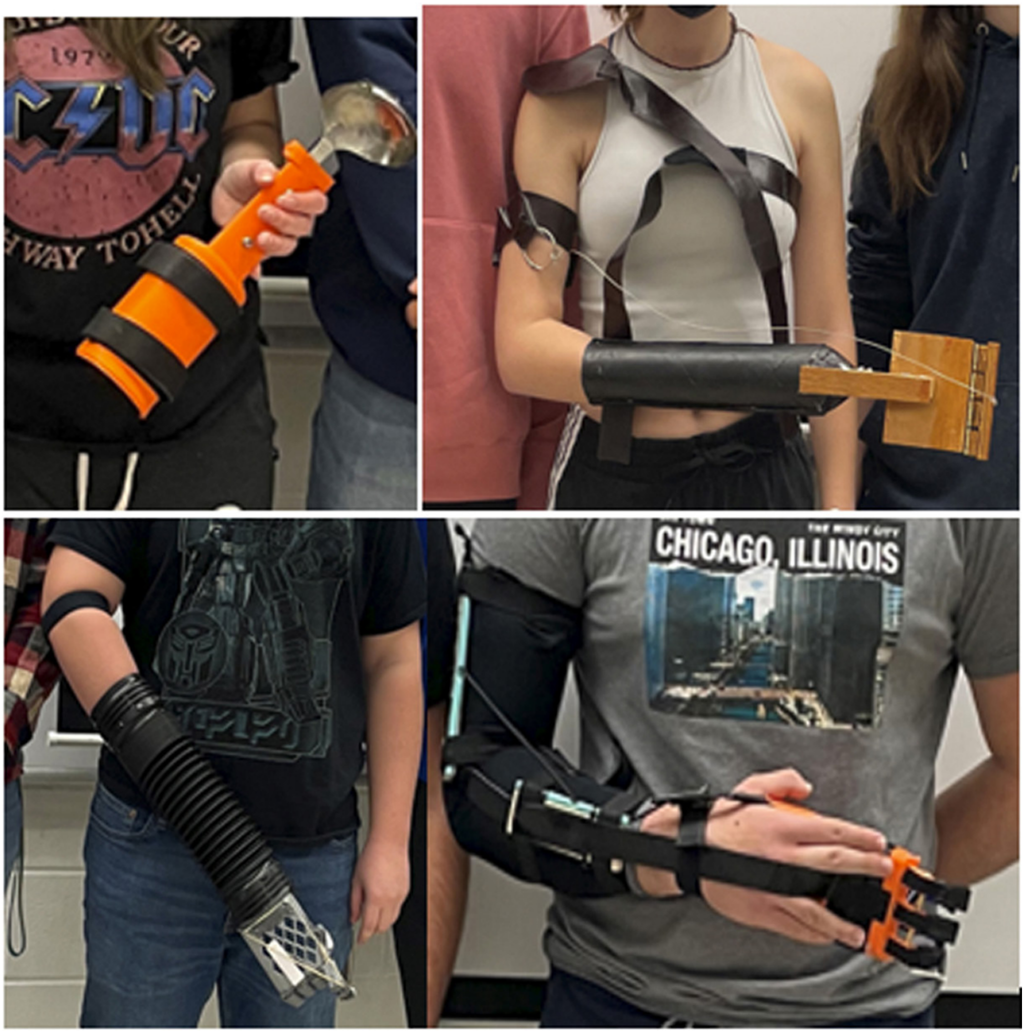

Fig. 1. Examples of student team products. Teams were tasked to design and construct a prototype trans-radial prosthetic arm for children

Throughout the semester-long project, students are exposed to the numerous sociotechnical influences and impacts on their engineering design experiences. For example, the heavy focus on understanding the problem, including research to explore previous developments in the context of societal needs and impacts, helps students appreciate the sociotechnical context of the technology they are proposing to develop. Similarly, clarifying the needs of their customers emphasizes the importance of empathy in the early stages of engineering design. Students demonstrate and evaluate their prototypes based on their ability to meet specific needs, such as low cost, the use of simple materials, and durability for an active child.

The project provides opportunities for students to develop an EM and practice EML skills throughout, in alignment with the primary 3C EML student outcomes of curiosity, connections, and create value, as illustrated in Table 1. Furthermore, the project also aligns with the KEEN framework by incorporating engineering thought and action through the application of creative and systems thinking to address societal and individual needs; collaboration through extensive and closely-knit teamwork; and communication through written documentation of their progress and oral presentation of their completed work.

3.4 Assessment instrument

Outcomes were assessed with the EML skills questionnaire, an online retrospective questionnaire that gathers information related to EML constructs with an orientation toward skill development (Table 2). The questionnaire was adapted from the work of Gorlewicz and Jayaram [40], who developed a series of post-only questions that were reviewed by other instructors and aligned with the outcomes developed by London et al. [87]. These outcomes served as the basis for the validated engineering student entrepreneurial mindset assessment (ESEMA) instrument [43]. The items used in this research were distributed among the 3C framework as follows: curiosity (four items); connections (nine items); and creating value (five items). Each item used a five-part Likert-type response scale ranging from one (strongly disagree) to five (strongly agree), with one neutral response. The internal consistency reliability of the survey, as measured by Cronbach's alpha, is 0.963, indicating high reliability [87].

Student responses to three open-ended questions administered at the end of the course provided additional feedback on students' perceptions of the project:

- Please describe one thing you LIKED MOST about the design project.
- Please describe one thing you LIKED BEST about the course.
- Please complete this sentence: The most valuable thing I learned from this course was…

3.5 Data collection and analysis

A total of 48 students completed the EML skills questionnaire through an online Google form after completing the design project. Quantitative data were compiled into Excel and analyzed using various methods within the statistical package for the social sciences (SPSS). Likert-type rating scales were converted to numerical values (ranging from 1 to 5) based on a predetermined preferred direction of response. This conversion was done to facilitate the calculation of summated rating totals and means for each item. Items were subsequently grouped into the categories defined above, and average mean responses for each student were calculated as simple means based on their responses to the items in each category. Post-only item responses are reported as overall category mean values as well as "positive response rates" to each item, determined by the percentage of students who strongly agree or agree.

Qualitative responses were imported into NVivo Pro 12 for thematic analysis, following a process similar to the guidance provided by [88]. A step-by-step process was followed for conducting the thematic analysis as per the guidelines given by Clarke et al. [89]. After familiarizing ourselves with the data, the responses were coded deductively using as a framework the 3C KEEN pillars: curiosity, connections, and creating value. The data and codes were further inspected to identify patterns and generate subthemes within the overall framework. Direct quotes have been excerpted from the reflections to enable readers to assess credibility, accuracy, and fairness [90].

4 RESULTS

4.1 Quantitative results

Student responses to the Likert-type items are summarized in Figure 2, which presents the mean values for each of the three EML skill categories: curiosity, connections, and creating value (n = 48). Scores on all three categories were generally high, with mean values ranging between 'agree' and 'strongly agree.' This indicates that, overall, the sociotechnical design challenge had a positive impact on students' EML skill development. The average scores on the curiosity subscale were significantly lower than the scores on both the connections subscale ($p < 0.001$) and the creating value subscale ($p < 0.01$). There was no significant difference between the connections and creating value subscales.

Details are provided in Table 2. Student responses were above four (agree) on all questions related to connections and creating value. In general, student responses were highest in the connections category, particularly on questions related to teamwork and understanding how design applications apply to real-world scenarios. Scores were also high, but slightly lower, in the "creating value" skill category. Students generally acknowledge the potential of engineering design to address societal issues and bring about improvements. Results in the curiosity skill category were not as impressive but still good, with mean responses above four on questions related to conducting research and enhancing critical thinking skills. Student responses were lowest on questions related to curiosity about innovative solutions and new discoveries.

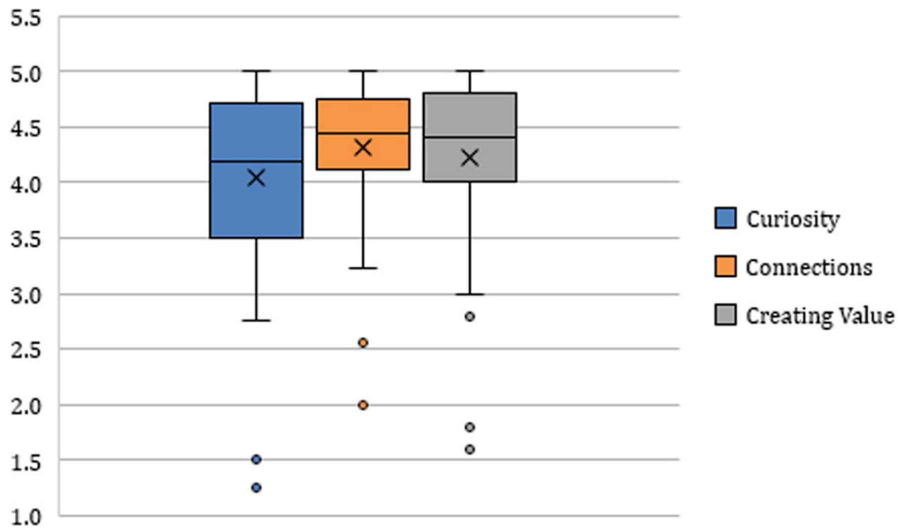

Fig. 2. Box plot showing the mean scores of students on three groups of questions that align with EML skills associated with each of the 3C's: curiosity (4.04 ± 0.84), connections (4.31 ± 0.62), and creating value (4.23 ± 0.76). Post mean scores indicate some degree development in each area of EML skills, with 'connections' ranked highest, and 'curiosity' ranked lowest

Table 2. EML outcomes: detailed mean responses to survey questions

	Did the Design Project and Associated Assignments Help you Improve your Various Engineering-Related Skills? Students were Asked to Indicate their Agreement with Each of the Following Statements.	Mean ± SD	%Agree, Strongly Agree	%Disagree, Strongly Disagree
Curiosity	I learned to conduct contemporary research and gather information.	4.06 ± 0.86	77.1	2.1
	The project improved my critical thinking compared to lectures.	4.26 ± 1.02	83.3	6.4
	The project helped me understand current technological trends and where the future technological trends are heading.	3.85 ± 1.17	64.6	10.6
	Working on this project helped me pursue self-discovery and piqued my curiosity about innovative solutions.	3.98 ± 0.98	68.8	6.4
Connections	The project encouraged me to 'think outside the box' and explore or investigate new ideas or novel technological changes.	4.28 ± 1.03	83.3	6.4
	The project helped me understand engineering design applications in real world.	4.54 ± 1.11	77.1	6.4
	I have improved my ability to share information with others.	4.25 ± 0.86	83.3	2.1
	I have improved my ability to collaborate with others (team members).	4.35 ± 0.89	87.5	4.3
	The project was an engaging way to learn.	4.40 ± 1.01	77.1	4.3
	The project helped connect information or ideas from different sources.	4.11 ± 1.00	81.3	6.4
	I have a better understanding of the challenges associated with teamwork.	4.42 ± 0.50	100.0	0.0
	I am more efficient at working in a team.	4.18 ± 0.75	91.1	2.3
	I have a better appreciation for the value of teamwork.	4.27 ± 0.54	95.6	0.0
Create Value	I have a better understanding of the engineering design process	4.51 ± 0.55	97.8	0.0
	I felt encouraged to explore opportunities and suggest solutions that would provide value to society.	4.04 ± 1.05	77.1	8.5
	The project helped me understand how design can create value and have a positive impact on others.	4.23 ± 0.97	87.5	6.4
	The project helped me understand how engineering design can meet the needs of society.	4.34 ± 0.97	89.6	6.4
	The project helped me broaden my perspectives in terms of pursuing ethical design practices.	4.06 ± 1.06	72.9	6.4

4.2 Qualitative results

Student responses to the open-ended questions, represented by the Word Cloud shown in Figure 3, affirm the overall significance of the design project and the broader sociotechnical learning outcomes that were accomplished. Several themes emerged. Most students mentioned the design project when asked what they 'liked best' about the course, and most indicated that learning about design and gaining experience in teamwork were the most valuable outcomes. Other commonly cited valuable outcomes included gaining an understanding of the broad sociotechnical nature of engineering and recognizing the significance of ethics in engineering. When asked about their favorite aspect of the design project, the most common responses were related to the project's hands-on nature. This was followed by the opportunity to collaborate as a team and the real-world relevance of the project.

Fig. 3. Word cloud created from student responses to open-ended survey questions

The themes that emerged from the student responses align well with the EML skill categories. Themes are identified and defined in the following sections, along with sample quotes for each theme. The EML skill categories, also known as primary themes, are further divided into sub-themes in order to gain a deeper understanding of students' perceptions regarding the development of the EM. For better readability and theme alignment, words and phrases have been bolded within each quote.

Theme 1—Curiosity. Sub-theme: exploration/discovery/inquiry—Students liked exploring new ideas and were curious to understand what their peers thought about it.

- "My favorite part of the design project was ***exploring new ideas*** and how ***people think*** differently about the same thing."
- "I liked the fact that we were able to ***rethink the design*** a lot. This allowed us to collaborate different ideas and see them unfold in the final prototype."

Sub-theme: problem solving mindset/attitude—Students applied critical thinking and communication skills to solve problems as they arose.

- "I enjoyed coming up with different ideas and ***fixes to problems encountered*** during the design project especially during the build process."

- "The most valuable thing I learned from this course was how to be an effective leader and handle ***communication problems*** in a group as well as the different ***problem-solving techniques*** that engineers use."

Theme 2—Connection. Sub-theme: skill application—Students connected their existing knowledge and applied new skills to develop and generate ideas and solutions for the problem.

- "The design project was definitely my favorite part of the course; it was great to be ***able to apply my engineering skills*** to a project."
- "My favorite part of the design project was being able to take engineering principles and the design process and ***applying them to an actual engineering problem***."
- "I liked the building process of our design. I had grown used to only visualizing my ideas, but now I was able to actually ***put them in action***."
- "What I liked best about the course was all the readings went along well with class making it easy to connect them to what we were talking about and ***be able to use*** that information."

Sub-theme: teamwork/group dynamic/collaboration—Students expressed appreciation for the opportunity to work in teams, where they could share and discuss information and diverse perspectives with their peers.

- "The most valuable thing I learned from this course was an understanding of the struggles of ***working with an engineering team***, and how hard it can be to coordinate with others about a project."
- "The most valuable thing I learned from this course was how to ***work together as a team*** and to work with people I was hesitant about working with at first."
- "The most valuable thing I learned from this course was the value of ***working with other engineers*** and looking at the broader picture when designing or constructing a project."
- "I enjoy ***working with a team*** and getting to get a physical product as a result."
- "I enjoyed meeting with my group the most throughout the experience and just starting the building process. Being able to ***work together*** was the best part."

Theme 3—Creating value. Sub-theme: growth mindset—Students approached problems from a different perspective.

- "The most valuable thing I learned from this course was ***how to view*** an engineering ***problem*** as more than just a technical one."

Sub-theme: social/societal impact—Students communicated engineering solutions in terms of their social benefits and created solutions that would benefit people and society.

- "I liked how we took an idea on paper and made it into a physical thing that ***anyone could use***."
- "The most valuable thing I learned in this course was the profound ***effects*** that engineers' [sic] decisions have on the rest of ***society***."
- "The most valuable thing I learned from this course was how my actions and the actions of engineers in general can have long time ***impacts***, so it is important to make sure everything is safe."

5 DISCUSSION

Students enter engineering programs with a very narrow understanding of what engineering is. Through their technology courses in middle and high school, students may have learned that "engineers solve problems." However, their exposure is typically more focused on the role of engineers in designing buildings, rockets, cars, and other machines. Many students have difficulty connecting and applying what they have learned in technical subjects [20]. They are often not aware of or do not appreciate the 'human side' of engineering or the importance of developing their communication skills [6]. Through this open-ended, interdisciplinary, team-based design challenge, first-year engineering students experienced firsthand the complex, iterative nature of engineering design, the importance of creativity and collaboration, and the strong connections between engineering and societal context. We sought specifically to explore the ways that designing from a sociotechnical lens impacted students' EM skill sets. Our findings show that the project developed students' EM skills across all three pillars of the KEEN 3C's framework. Skills within the connections and create value pillars were developed to a greater extent compared to those in the curiosity pillar. Outcomes in these first two categories overlap most significantly with the outcomes related to students' ability to comprehend and value engineering within a sociotechnical context.

Challenging students with real-world problems has been shown to effectively highlight the importance of design as a process, helping students appreciate the need to fully understand the problem and consider a range of alternative solutions [20]. Previous studies have also demonstrated that framing engineering and engineering problem-solving through a sociotechnical lens can increase first-year students' sociotechnical thinking and their awareness of engineering as a creative, interdisciplinary profession [62] [63] [91]. In the present study, multiple students expressed that their enhanced comprehension of the sociotechnical aspects of engineering was the most valuable component of the course. This was evident in their responses to the open-ended survey questions at the end of the course:

> "The most valuable thing I learned in this course was the profound effects that engineers' [sic] decisions have on the rest of society."

And specifically in terms of public safety:

> "The most valuable thing I learned from this course was how my actions and the actions of engineers in general can have long time impacts, so it is important to make sure everything is safe."

The impact of a sociotechnical-framed design challenge on students' EM skill development is less widely studied. However, research has shown that it generally has positive impacts on students' ability to think with an entrepreneurial mindset [80]. It also makes students more aware that there are often multiple co-existing solutions to complex problems and encourages them to give greater consideration to the value their engineering solutions might provide [79]. Our findings show that, overall, students developed skills in all three pillars of the KEEN framework, although the outcomes were stronger in certain areas than in others. Overall outcomes related to connections and creating value ranked higher than those related to curiosity (Figure 2). On average, 73% of students agreed or strongly agreed that the project helped develop their curiosity-related skills. While several studies demonstrate the effectiveness of EM activities for exposing students to EML and improving their awareness of EML concepts [54], enhancing their intrinsic motivation and self-efficacy [51] [58], and facilitating learning beyond the curriculum [41] [56], studies that have specifically assessed the outcomes related to collaboration, communication, and critical thinking (3C) from integrating EM content are somewhat mixed. For example, Gorlewicz and Jayaram [40] integrated EM content into a three-course dynamics and controls sequence, which was taught to sophomore to senior students. They also discovered that students had lower outcomes for questions related to the curiosity pillar. In contrast, Zhu [57] integrated EM content into a hands-on project in a junior-level mechanical engineering class. Through a thematic analysis of the final project deliverables, Zhu found a fairly balanced distribution of outcomes across the three C's. These differences could stem from variations in assessment strategies. Zhu's holistic analysis of student projects may not have fully captured the students' responses to specific curiosity-related skills, as outlined in the Likert surveys utilized by Gorlewicz and Jayaram [40] and in this study. Gorlewicz and Jayaram [40] found low responses to skill development questions related to generating inquiries, meeting needs, and understanding technological, societal, and economic trends. Similarly, in our study, the skills that students reported as being least developed were related specifically to the pursuit of self-discovery and peaking curiosity about innovative solutions (69% agreed or strongly agreed) and understanding current and future technological trends (62% agreed or strongly agreed). These skills were primarily the focus of early activities, such as team formation, brainstorming, and research (see Table 1). Overall, less time was allocated to these activities compared to later stages as students delved deeper into their projects. Although the 'build and test' phase should by its very nature provide opportunities for students to develop curiosity, it is possible that the novice level of first-year engineering students resulted in an oversimplification of this process, which might engage older students in more self-discovery and innovation. Indeed, previous research has shown that novice problem solvers tend to rely more on trial and error. They generate an idea and immediately implement that decision, compared to their more experienced counterparts, who tend to spend more time analyzing ideas before implementing them. Experienced problem solvers also keep their options open, question their data more, and refer more to past designs as they move forward [92].

Skills in the other two pillars of the 3-C framework were more fully developed. On average, 85% of students agreed or strongly agreed that the project improved their overall skills related to creating value. Most notably, it helped them understand how engineering design can create value and have a positive impact on others (88%), as well as meet the needs of society (90%). Relatively high responses in this category align with their exposure to the links between engineering and society in general, as described above. These findings support the earlier, more general findings by Choi-Fitzpatrick and Hoople [80] and Bertoni [79] as well as our own earlier work [62] [63]. Still higher was the degree to which the design project developed their skills related to connections, with 86% agreeing or strongly agreeing to the aggregated questions in this category. On average, 83% agreed or strongly agreed that they were encouraged to 'think outside the box and investigate new ideas and novel technological changes.' The strongest agreement was reported on questions related to the development of their teamwork skills: sharing information with others (83%), collaborating (88%), being efficient at teamwork (90%), appreciating the value of teamwork (95%), and understanding challenges associated with teamwork (100%). Similar findings were reported by Gorlewicz and Jayaram [40]. The students agreed most with connections questions that were related to developing partnerships and team-building skills, acquiring new knowledge and perspectives, and meeting societal needs in the creating value category. Interestingly, 82% of students reported that the project helped them connect information or ideas from different sources. This percentage is slightly higher than their response to a similar question in the curiosity pillar, which focused on skills for conducting research and gathering information (77%).

Within the 3C framework, outcomes related to the connections and creating value pillars align most closely with the course- and ABET-learning outcomes that aim to develop students' understanding of engineering and engineering design as a sociotechnical endeavor. EM skills related to creating value parallel the 'user-centered approach' of design thinking, which considers first and foremost the impact of engineering decisions on key stakeholders including society, communities, and the environment [68] [69]. The overlap with sociotechnical thinking is evident. Within the connections area of the framework, the most significant outcomes relate to peer-to-peer interactions, collaboration, information sharing, and connections to real-world applications. Given the high number of students who referred to teamwork in the open-ended survey questions (17 out of 40 indicated that learning to work in a team was the most valuable outcome of the course; 10 out of 48 indicated teamwork as the best aspect of the design project), the strong positive influence of the project experience is evident.

Overall, student comments at the end of the semester indicate that they were highly engaged in the project. The first-hand experience of applying the design cycle to solve a real-world problem was identified as one of the main factors contributing to this engagement. With regards to teamwork, students enjoyed "exploring new ideas and understanding how individuals have different perspectives on the same topic." Another student mentioned, "What I appreciated the most about the design project was that it taught me how to collaborate effectively within a team and leverage everyone's skills to create a high-quality design."

Student comments about the design in general were similarly positive. One student mentioned, "*The feeling of completing the arm felt very good*." Another student appreciated the opportunity to rethink the design extensively. "*This allowed us to collaborate different ideas and see them unfold in the final prototype*."

6 CONCLUSIONS

These findings indicate that, overall, offering first-year students the chance to engage in an open-ended design challenge framed within a sociotechnical perspective is crucial in helping them develop their EM skills. Broadly speaking, the project enhanced their awareness and understanding of engineering as a collaborative, interdisciplinary endeavor that is driven by and has far-reaching consequences for sociocultural and environmental stakeholders. Additionally, they developed important skills that enable them to approach problems with an entrepreneurial mindset, embracing complexity, working collaboratively, and ultimately improving the value of people's lives. These outcomes all address the needs identified by the National Academy of Engineering [7], as well as accreditation boards [21] [22], in order to equip engineering graduates with the skills necessary to effectively address the complex and challenging problems that the world faces today.

Students indicated that, overall, the project helped to enhance their EM skills across all three pillars of the KEEN 3-C framework. However, they reported greater development in skills related to establishing connections and identifying solutions that create value, compared to their skills for exhibiting curiosity. These findings are not surprising, given the project's strong emphasis on the significance of sociocultural, political, and economic factors in engineering problems and engineering design. The project also highlights the importance of prioritizing stakeholder-driven design solutions and emphasizes the need for interdisciplinary teamwork and collaboration. Despite the relatively low overall response rate for curiosity skills, 84% of the students agree or strongly agree that the project helped improve their critical thinking skills (mean 4.26 ± 1.02). Students reported that the skills they developed most were the ability to 'think outside the box' and explore new technologies (83% strongly agree/agree; mean 4.28 ± 1.03), their understanding of the engineering design process (mean 4.51 ± 0.55) and design applications in real world settings (mean 4.54 ± 1.11), understanding how design can meet the needs of society (mean 4.34 ± 0.97), create value and have a positive impact on others (mean 4.23 ± 0.97), and teamwork-related skills such as collaborating with others (mean 4.35 ± 0.89) and sharing information (mean 4.25 ± 0.86).

This exploratory study was conducted over the course of one semester with two relatively small sections of a first-year engineering course. Due to the small and relatively homogeneous sample (consisting mainly of white males), the findings of this study are largely exploratory. While they do support earlier findings, caution should be exercised when generalizing these results to a larger and more diverse population. Moreover, the post-only data collection relies mostly on students' reflections when looking back on the experience. While a post-only reflective assessment strategy has clear benefits, such as eliminating the possibility of response-shift bias [93], the technique is prone to biases caused by the fallibility of human memory (recall bias) as well as the possibility of participants to responding in a way that is more socially desirable [94].

Future work extending the analysis to a larger number of sections, with a wider range of project topics will help deepen our understanding of the potential interactions between framing engineering design challenges from a sociotechnical perspective and the facilitation of students' development of EM skills. Additional questions will also allow us to investigate the impact on students' motivation and self-efficacy. Curricular changes aimed at increasing the focus on activities that involve exploring technology trends and considering multiple perspectives in a rapidly changing world, as well as promoting self-growth through independent and self-directed learning, may contribute to enhancing students' development of EM skills related to the curiosity pillar of the Keen framework.

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