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The Integration of a Maker Program into Engineering Design Courses*

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The integration of making activities into engineering curricula has the potential to increase students' self-efficacy and allows for participation in problem-solving, design and fabrication activities. In this study, we discuss the authenticity of the learning environment of cornerstone design courses that have integrated making activities as a central theme. We conducted fourteen interviews with seven students in two different teams during their learning experience in a second-year cornerstone design course with a making curriculum. Drawing from our interviews and observations of the students, we discuss the authenticity of the learning environment and students' experiences within it. We also discuss the challenges that students go through as they are completing their projects and the implications for engineering instructors who are interested in integrating making activities into their courses. We describe how situating formal design courses in a makerspace environment offers students an authentic design experience, with opportunities to develop and practice authentic engineering skills and to solve problems that are similar to workplace problems. It also helps students increase their confidence in their design and problem-solving skills and exposes them to multiple topics and disciplines.

Keywords: authentic learning; situated learning; engineering design education

1. Introduction

Engineering, like any other professional occupation, has a social body of knowledge that is created through a complex landscape of practices and people – including regulations, management, professional practitioners, researchers and theorists – that inform and influence each other [1]. Engineering education as a practice needs to be aligned with the 21st-century requirements of engineers, as they need to be trained to be able to adapt to work in a global economy with constant and rapid changes [2, 3]. These changes include the rapid technological innovations that are empowering individuals, organizations and states [3, 4]. However, these innovations also present complex challenges, discontinuities and tensions [5]. Engineers today need to possess strong analytical, communication and planning skills; they also need to be knowledgeable of business and management principles to solve problems in an original and creative way [2, 6, 7]. In response to these challenges, engineering educators have been developing innovative teaching approaches that introduce students to the engineering profession in engaging and meaningful ways [8]. Methods include experiential learning opportunities, cooperative, project-based and problem-based learning, and the infusion of design throughout the curriculum [8, 9]. These innovations in teaching aim to help students construct and apply knowledge and skills that will help them solve interdisciplinary, complex real-world problems throughout their career [10–12].

The introduction of maker activities and maker pedagogies in engineering education is an especially promising innovation in teaching [13–15]. Integrating making activities into formal educational settings helps to create learning environments that place learners at the center of the learning process as they turn from passive consumers of knowledge into producers. Making activities also help increase students' self-efficacy [14] and interest in science, technology, engineering and mathematics (STEM) fields [16]. Moreover, making activities provide a powerful context to introduce real-world problems into the engineering curricula [13] and integrate the socio-emotional and disciplinary dimensions of learning [16]. Furthermore, the incorporation of a maker curriculum in engineering education also gives students an opportunity to participate in problem-solving, programming, design and fabrication activities [14] and exposes them to design-based activities that teach digital literacy and design thinking, which in turn supports students' ability to deal with failure and engage in the reflection and iterative processes that are integral to design projects [17].

Despite the enthusiasm for the integration of making activities into education and the growing body of research on the opportunities making activities provide for engineering education, there has been little research on the development of making programs in engineering, and there remains a need for a more in-depth analysis of students' learning experiences with making activities in formal educational contexts [14, 18]. This paper

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explores whether the introduction of a maker program in a cornerstone engineering course can offer an authentic learning experience of engineering design. We start by describing the course and setting where students learn. We then present a qualitative analysis of the authenticity of the learning environment and illustrate ideas and considerations for designing authentic learning approaches for teaching engineering design.

2. Background

2.1 Authentic Learning

Authentic learning is a pedagogical model that has been conceptualized as an approach to design and promote effective and engaging learning environments [19, 20]. The theoretical foundations for authentic learning are found in situated cognition or situated learning [21, 22] and legitimate peripheral participation [23]. Unlike learning theories that define knowledge as an integral, self-sufficient construct that is independent of the situations in which it is learned and used [24], situated learning theory argues that learning and cognition are inextricable from the environment. From this perspective, knowledge is emergent and fundamentally situated in activity [22]. Knowledge is provisional, mediated and socially constructed [25], [26] and is embedded in "doing" rather than accumulated [27]. In this view of learning, "knowing" is a "relation among communities of practice, participation in practice, and the generation of identities as part of becoming part of ongoing practice" [15, p. 157].

Activities within an authentic learning environment are coherent, meaningful and purposeful activities of the domain or culture [22]. They reflect the complexity of knowledge and its construction and practice in real life [20, 28]. An authentic learning environment must offer opportunities for learners to construct knowledge collaboratively, explore multiple roles and perspectives, access expert performances, reflect on what they are learning, find mentorship and guidance, and articulate their ideas [20, 28]. These learning environments open opportunities for learners to cultivate skills that are difficult to cultivate on their own, such as the judgement to recognize reliable and unreliable information, patience to follow longer arguments, creative ability to recognize relevant patterns in unfamiliar settings, and flexibility to work across disciplinary and cultural boundaries to generate innovative solutions [28]. Moreover, authentic learning environments also enable students to practice critical thinking, problem-solving and public speaking skills [29]. Examples of authentic learning approaches include personalized learning, project-based learning and community-based learning [29].

Standards of authentic learning and achievement stem from a belief that education should extend beyond the transmission of isolated facts and skills to enabling the development of in-depth understanding and complex problem-solving skills that are valuable to both students and society [30]. Wehlage, Newmann and Secada [31] developed standards for pedagogy and achievement as a research tool to guide school reform. They defined authentic achievement as "intellectual accomplishments that are worthwhile, significant, and meaningful" [30, p. 23]. Their vision for authentic achievement entails the construction of knowledge through disciplined inquiry using prior existing knowledge and striving for in-depth understanding to produce discourse and products that have value beyond success in school.

In the context of engineering education, authentic learning models have been used to replace traditional approaches – which expose students to simple, unrealistic hands-on activities as part of a guided engineering challenge – with authentic approaches that provide opportunities for student to use industry-quality materials, tools and resources to solve authentic engineering problems [32]. The use of authentic learning models in engineering design courses also provides ideal opportunities to engage students in authentic engineering communication through meaningful assignments and emphasis on the situations that engineering students might encounter in the workplace [33]. Moreover, in engineering education, authentic learning models are used to provide students with multiple opportunities that promote deliberate practice and allow students to practice their skills on authentic tasks [11].

2.2 Making as a Vehicle for Authenticity

The interest in improving the design component of engineering curricula coupled with a societal interest in the design and fabrication of physical objects with the rise of the maker movement has been driving engineering schools to invest in makerspaces for engineering students to learn, work and share [13]. These spaces provide a collaborative and interdisciplinary learning environment [34, 35] where students engage in design, prototyping, testing and/or manufacturing of artifacts rapidly, while using engineering knowledge, technology and tools [36]. Makerspaces provide engineering schools with an opportunity to infuse design throughout the curriculum by supporting project-based learning in a space where a learning community and resources are readily available on campus [34]. Makerspaces also have the potential to expose engineering students to concepts of technology acceleration, entrepreneurship, manufacturing and programming and to help them improve their design and practical skills through the practice of engineering knowledge and skills [34, 35]. Wilczynski, Zinter, Wilen [34] proposed that many historical design education challenges – such as teaching practical engineering skills in a collaborative, interdisciplinary environment, improving engineering students' design skills, increasing their confidence in their skills, and improving and increasing the design component in engineering curricula – can be addressed when formal engineering design courses are hosted in academic makerspaces.

Making as a pedagogical approach lies in learning theories of constructionism and constructivism. Constructionism [37] suggests that learning is supported through the construction of physical objects; constructivism suggests simply that knowledge is constructed through activity [16, 38]. Although there is no consensus on what counts as making in an educational context [18], for the purpose of this article, making activities are defined as a class of activities focused on designing, building, modifying and/or repurposing material objects, for playful or useful ends, oriented toward making a "product" of some sort that can be used, interacted with, or demonstrated [39]. The current published literature on making educational programs can be classified into three main categories: making as means for entrepreneurship and/or community activity, making as STEM pipeline and development of workforce skills, and making as educational practice for inquiry-based learning [16].

In their literature review of making and tinkering, Vossoughi and Bevan [16] synthesized findings from published literature on making and noted three ways that making can be valuable for education. First, making programs can be designed to encourage students to participate in STEM-related programs by supporting new intellectual dispositions, identities and future trajectories; by connecting making to existing familiar practices; and by turning students from being passive consumers of knowledge to becoming active producers. Second, making programs can support young people's learning and development by contextualizing STEM concepts and practices in meaningful activities; by cultivating opportunities for interdisciplinary learning environments; and by encouraging students to assume intellectual risk and embrace failure while tinkering, designing and solving a problem and helping them rebrand that "failure" as essential to the iterative and experimental process of making. Third, making programs can help create a supportive community of learners by encouraging collaboration and the sharing of tools and ideas, as well as by creating an environment where the roles of experts and novices are fluid.

A few studies have described the integration of making activities into engineering curricula. One study explored how making activities are integrated into courses at the faculty of engineering at Arizona State University. In a robotics course, students created a robot using a kit they purchased, and in an engineering statistics course, students created physical or media-focused artifacts that could provide context to their understanding of practical statistics [40]. In an interesting approach to the integration of making activities into engineering curricula, Texas A&M University at Qatar has integrated making activities into its technical writing component of the curriculum by asking students to develop a prototype in an area of engineering design using rapid prototyping tools and to complete several writing and communication assignments, in an effort to provide problem-based assignments that make the technical writing course more relevant and prepare students for their capstone course [41].

The purpose of this article is to explore the use of making activities as a vehicle for designing an authentic learning approach to teaching and learning in engineering design in the first – and second-year levels of an engineering program. We provide a case study description of the cornerstone design program at the University of Ottawa, Ontario, and the approach we use to introduce engineering students from various disciplines to engineering design. We also explore students' learning experience in the course through a qualitative study that identifies what students learned in the course and what challenges they faced, in hopes of improving the program and assessing the value of integrating making activities into the engineering curriculum.

3. Centre for Entrepreneurship and Engineering Design (CEED) Facilities

Making activities are integrated into the engineering curriculum at the University of Ottawa via the Centre for Entrepreneurship and Engineering Design (CEED), which is housed in the STEM building and features seven facilities. They include an academic makerspace with digital and physical prototyping tools, a machine shop with traditional prototyping tools, the Manufacturing Training Centre (MTC), the MakerLab (makerspace training and design course lab space), training centers for all types of equipment, and collaborative spaces.

Undergraduate students of all years and graduate students have free access to all CEED facilities to gain knowledge and skills as they work on personal projects and school projects. The spaces are open to all students of the University during the week, and the makerspace is open to the local community as well on Sundays. The makerspace is open eight hours a day; its staff started as undergraduate students but now include graduate students and recent alumni. The term "academic makerspace" is often used to describe university campus makerspaces and distinguish them from industry, community, and K-12 makerspaces [42]. The University of Ottawa established its own makerspace to provide a physical location that would cultivate social networks that support curricular and extracurricular activities, foster collaboration and peer-learning, offer an experiential learning environment [42], increase students' self-efficacy through engagement with fabrication technologies [43], and provide a learning environment that blends traditional and digital skills with arts and engineering and that has multiple entry points for participants that lead to innovative combinations and uses of disciplinary knowledge, helping to break down disciplinary boundaries [44, 45]. These aspects of the makerspace contribute to what sets making activities apart from traditional hands-on projects with prototyping. Originally launched in 2014 with a few pieces of technology that included 3D printers, Handibots® (CNC handheld routers), a few hand tools and computers, the makerspace has since grown to more than four times its original size as it has added new equipment and moved to a newly constructed STEM building.

4. Design of Making Cornerstone Design Courses at the University of Ottawa

Based on the rapid growth of makerspaces in educational institutions, and aiming to seize the potential benefits that the maker movement can bring to engineering curriculum at the undergraduate level, cornerstone design courses with a making curriculum as a central theme were developed at the first- and second-year levels at the University of Ottawa. The courses were designed to provide students with a hands-on, team-based introduction to engineering design where they are tasked with tackling a problem, identifying its constraints, establishing the corresponding criteria, and adhering to the criteria and constraints to enact a design process for creating a practical solution to the problem [32].

The courses were introduced initially in 2016 as electives for students of all engineering disciplines in the faculty. The first-year course is a hands-on, team-based introduction to engineering design for first-year engineering and computer science students. Topics covered in the course include design thinking, engineering design process, prototyping, engineering economics, safety, ethics and project management. The second-year course is a hands-on, team-based introduction to product development and management principles and their impact on social and economic aspects of engineering practice. The course covers topics such as creativity and innovation, product development process, engineering project management, market evaluation and identification, engineering economics, and technology entrepreneurship.

Students in both courses are required to work with a client from the local community to devise an engineering solution for a problem the client is facing and engage in a process of multiple iterations to produce a functioning final prototype by the end of the course that meets the client's needs. Students registered for the first-year course are divided into three sections, each with a different project, such as building a zero-net-energy greenhouse, creating a hydroponic system or creating a robot for water sampling. Students registered for the second-year course are required to solve an accessibility problem facing a client from the local community, such as creating a hand sanitizer for a client with limited motor control, a device to teach children with disabilities how to skate, a snow removal device that can be installed on a wheelchair for a client with cerebral palsy, a portable lightweight ramp, a portable wheelchair curtain, an assistive feeding device, a wheelchair robotic arm, or smart curtains for windows in long-term care residences.

The theme for the first-year course changes almost every semester and is different between sections. The theme for the second-year course is always accessibility. Clients are diverse, ranging from individuals to organizations like hospitals, and all have different needs. Students in the second-year course have more choice with their projects, as teams pick their top three choices and then the professor assigns the projects. Students in the second-year course are also required to meet with their client outside campus. All of the projects situate the students in a learning environment where they need to find an engineering solution for a problem faced by their clients and produce a final prototype that corresponds to the clients' needs, taking into consideration the financial and time constraints.

Students also have to participate in a weekly lab session at the University of Ottawa's makerspace that aims to integrate making activities into the engineering curriculum, encourage students to participate in an environment with diverse learning arrangements [45] and facilitate their entry into the students' maker community of practice (CoP) that has formed within the makerspace since its opening. Labs are divided into two portions. In the first portion, students are introduced to various rapid prototyping and engineering tools. Labs are held in the makerspace, where students are introduced to technologies such as sheet metal processing, SolidWorks, 3D printing, Arduino, printed circuit board (PCB) design, soldering and mobile app development. At the end of the first portion of the labs, a chariot race is organized as a fun activity at the makerspace, where students demonstrate the functionality of their small chariots. In the second portion of the labs, students work on developing their prototypes. Although these courses have been designed to offer authentic learning opportunities, it was not clear whether, or to what extent, students benefit from making as a pedagogical approach. We wanted to contribute to the literature on making by providing observations on what happens in a learning environment that uses making as a pedagogical approach.

5. Current Study

5.1 Research Question

This study explores whether the introduction of making projects and activities into engineering design courses creates conditions that open possibilities for authentic learning. Further, we seek to understand the challenges that students face in courses based on making activities.

5.2 Method

In qualitative research, the researcher is the data collection instrument [23, p. 247]. Hence, prior to the discussion of the methods used in the study in detail, the reader deserves to know the identity, interests and motivations of the first author of the paper who conducted the interviews. The researcher in this study is a PhD candidate at the University of Ottawa focusing on the impact of the maker movement on engineering education. As a doctoral candidate, his prior research in establishing makerspaces in engineering schools and their impact on forming student-maker communities of practice led to his interest in providing more information about how engineering educators can integrate making programs into their curriculum and in providing an in-depth understanding of students' learning experiences in courses that have successfully integrated a making program into undergraduate engineering courses.

In the following sections, we describe how the participants were selected and how the data were collected and analyzed.

5.2.1 Participant Selection

We used stratified random sampling to select information-rich cases, as this allowed us to get an in-depth understanding of the students' learning experiences in the course under study. This sampling strategy divides a population into sub-populations, and then a random sample is selected from each sub-population [47]. The sample design was constructed to represent the diversity of the engineering student population at the University of Ottawa, with teams were selected to be diverse in terms of their engineering discipline, gender and academic achievement as measured by the students' self-reported cumulative grade point average (cGPA).

Initially, we administered a survey in the second week of the semester to all students in one lab section (n = 18) that asked students their name, gender, previous engineering design course experience, identification as makers, year of study, and engineering discipline. Of the 18 students, we decided to follow seven students (female = 3; male = 4) who belonged to two student-teams out of the four teams in this particular lab section. We limited our sample to teams in one lab section because different lab sections have different teaching assistants and project managers, and we wanted to make sure the instruction team was consistent for all the participants of the study.

The participants selected for this group were chosen to represent the engineering disciplines available at the faculty. We chose students from both genders, from the first- and second-year programs and from different engineering disciplines. We also considered students' identification as makers to understand the experience of those who identify as makers and those who don't. We also wanted to make sure our sample varied in terms of academic performance to understand if the learning experience in the course is similar for students with high and average academic achievement. We conducted our interviews and discussions with students during their lab hours in the makerspace.

Team Mystique:

The first team we followed was working on a project as part of the Make-a-Wish foundation, a program that aims to realize wishes for children with critical illnesses. The team was asked to create a guitar that would allow a girl who is paralyzed on one side to learn how to play the guitar. The technologies involved in creating the device included microcontrollers, programming, computer-aided design (CAD) and 3D printing. The students knew each other, and all four of the team members were high-achieving students who told us they chose to work together because they trusted each other to commit to the project work.

- Lisa (all names are pseudonyms): a second-year civil engineering students who had taken the first-year cornerstone design course in her first year of study at the faculty of engineering. Lisa did not share her cumulative grade point average (cGPA) with us. Lisa registered for the course because she had enjoyed the first-year cornerstone course and because her friends were going to take the course, so she could pick her own teammates.

- Dean: a third-year software engineering students who had also taken the first-year cornerstone design course in his first year of study at the faculty of engineering. Dean reported a cGPA of 9.40 out of 10. Dean had not completed his second-year elective course, and so he chose this one as an elective because he had enjoyed the first-year capstone design course and he wanted to work with John, since they had worked together in the previous cornerstone course. His learning goals were that he wanted to develop his electronics and programming skills with hands-on experience.
- John: a second-year civil engineering student who had taken the first-year cornerstone design course in his first year of study at the faculty of engineering. He reported a cGPA of 8.00 out of 10. John wanted to improve his technical skills, learn how to put things together and improve his CAD skills.
- Nora: a first-year engineering student who had transferred from the faculty of sciences to engineering this year and registered for both cornerstone design courses at the same time. Nora did not share her cGPA with us. Nora had no expectations walking into the course. She did, however, want to learn about 3D printing and about designing and creating an object.

Students generally indicated they registered for this course because they had enjoyed their first-year cornerstone design course and because they walked into the course knowing they would be able to work together. Nora, who had just started her first semester in engineering school and had registered for both first-year and second-year cornerstone design courses, indicated that her motivation to take the course was because it was part of her program.

Team Sunday Funday:

The second team we followed was working on creating a wheelchair assist device that would help a wheelchair user to self-propel herself using the device instead of using her arms. The technologies involved in creating the device included microcontrollers, programming, and 3D printing/machining. The students chose each other because they were friends.

- Oscar: a second-year civil engineering student who had taken the first-year cornerstone design course in his first year of study at the university and reported a cGPA of 7.8 out of 10. Since Oscar had already taken the first-year cornerstone design course, he knew what he was signing up for. He expected to learn a lot and thought the course would teach him to "put yourself in other people's shoes."
- Tim: a second-year civil engineering student, who had taken the first-year cornerstone design course in his first year at the faculty of engineering. Tim reported that his cGPA was 6.8 out of 10.
- Anna: a second-year mechanical engineering student. She had never previously participated in any design course. Anna did not share her cGPA with us.

Students had two options to choose from as their elective course for this semester, and they chose this course over Engineering Economics because they thought they would learn a lot while helping someone. They also indicated that they didn't like the scheduling of the other offered course, which had a three-hour evening lecture.

5.2.2 Data Collection & Analysis

We collected the data reported in this study over the course of the fall semester of the 2018–2019 academic year. The first author conducted seven semi-structured interviews with each team. The semi-structured nature of the interviews allowed for conversations between the interviewer and the participants that helped them reflect on their experiences in the course and discuss how their projects were progressing. The total time for these interviews was 100 minutes for Team Mystique and 80 minutes for Team Sunday Funday. Interviews were audio-recorded in the campus makerspace. Interviews were transcribed verbatim in the same week they were conducted. Interview transcripts were shared with the students in each team, and the students were offered the opportunity to make changes or omissions after receiving the transcripts.

In-depth interviewing was chosen as the data collection method for the study because it offers open-ended, in-depth exploration of an aspect of life that is of interest to the researchers and that the interviewee has substantial experience with and insight into [48]. Our goal was to collect data that could help explain a phenomena in a bounded context [49]. Written consent was obtained from all participants in the study. The interviewer used several tactics to encourage the participants' honesty and to ensure willing participation, such as asking participants if they would be willing to be interviewed throughout the semester and informing them that the interviews would be audio-recorded. They were also made aware that they could withdraw from the study at any time. Moreover, the interviewer had no institutional power over the participants, such as being a member of the course's instruction team or being introduced to the students by a member of the course's instruction team. These tactics helped ensure that only those who were genuinely willing to participate in the study and offer data freely were included in the study [50].

Initially, the interviewer built rapport with the participants and introduced the study objectives to them. In the first interview with each team, we asked participants to describe their project choice and how they formed their groups, which allowed students to talk about their personal learning objectives, motivation to work on the project and past experiences in a collaborative learning environment. Throughout the semester, we asked students in every interview what they thought about their progress in the course, day-to-day activities related to the project, interactions with the client and the course's instruction team, plans for the project, team dynamics and lessons learned from their project experience. Asking about these themes in every interview allowed the students to describe their learning experiences as they were going through each phase of the design process. In the last interview with each team, we asked students about the final feedback they had received from the course's instruction team, their intent to continue working on the project, the lessons they had learned from the course, their identification with engineering design and what recommendations they had to improve the course.

Through the semi-structured interviews, the interviewer asked follow-up questions to students' responses to uncover more details about individual students' experiences, objectives, challenges, activities and feelings. The interviewer often repeated the students' answers back to them to ensure the accuracy of the data and to help participants provide more information about their experience.

5.2.3 Data Analysis

Based on the nature of the study question, grounded theory was used as the qualitative analysis strategy [51]. We were seeking to explain and reach a higher level understanding of the engineering students' learning experience in design courses with making projects, and grounded-theory methods allow for systematic yet flexible guidelines for collecting and analyzing qualitative data to construct theories grounded in the data [51]. Since we were trying to assess the authenticity of the learning experience that can result from the integration of making activities into a formal engineering education setting, we wanted to allow the ways and processes in which students learn emerge from the data rather than make assumptions about their learning process. We conducted the data analysis using NVivo® software and kept notes on the software, on Microsoft Excel® spreadsheets and on paper.

Grounded-theory researchers collect data and analyze it simultaneously from the initial phases of research [48]. We interviewed students every week and simultaneously analyzed the data. After every two interviews, debriefing sessions with a professor of engineering design at the University of Ottawa were conducted to ensure credibility [50], analyze the data, discuss our initial findings, adjust research questions and/or introduce new questions according to ideas and themes that were emerging from the interviews collected.

Grounded-theory coding consists of at least two phases: an initial phase that involves a close reading of the data collection and analysis, remaining open to all the possible theoretical directions indicated by the reading of the data, and a focused coding phase, where the researcher synthesizes and explains larger segments of data [52]. To analyze the data, we created a "start list" of codes after the first week of interviews from our conceptual framework and research questions [52]. The start list of codes consisted of codes related to criteria for authentic achievement from Wehlage, Newmann and Secada [31], elements of an authentic learning environment from Herrington, Reeves, and Oliver [21] and general skills we hypothesized the students would be honing in their project experience. Initially, we used structural coding by applying either a content-based or conceptual phrase to segments of data that related to research questions [53, 54]. We then followed up with initial coding where we used process and In Vivo coding to break down the interview transcripts into discrete parts and compare them for similarities and differences [54]. We then proceeded with coding the data inductively, creating sub-codes and modifying those on the original list. To transition to the second phase of the coding process, we performed code mapping, where we reorganized codes into a select list of categories, and similar codes were merged to create three central themes:

- Authentic achievement codes: We created this category to understand how students constructed new knowledge and used existing prior knowledge in completing their project, as well as how they articulated concepts and ideas they were learning and what values they assigned to their learning experience (i.e., construction of new knowledge: skills, research, etc.; value: experiential learning, help someone, etc.; disciplined inquiry: articulation, in-depth understanding, etc.).

- Impact of the learning environment on students' skills codes: We created this category to capture all codes that could indicate students' improvement in technical and soft skills. The codes captured in this category included attributes related to problem-solving and design skills (i.e., ideation, dealing with uncertainty, meeting design constraints, reflection, collaborative and peer learning).
- Challenge codes: We inductively created challenge codes to capture students' perceived challenges in this learning environment (i.e., time management, stress and communications with the client).

We constantly refined the codebook as we analyzed the interview transcripts. After establishing our final codebook we conducted a test of inter-rater reliability according to Miles & Huberman [52, p. 64]. We invited a researcher who wasn't a part of this study and new to the codebook to independently code two randomly selected interviews (14% of the data); inter-coder reliability was 84.8%. During the last phase of the analysis process, we created categories of categories to gain insights into our findings and identify patterns and connections in the data. After updating the conceptual framework of the study, we summarized the study codes and findings and discussed them during debriefing sessions. We revised our findings, identified patterns and themes and discussed the findings in the context of engineering design education. We stopped data collection at the end of the semester before the final exam of the course.

5.3 Findings

In the findings, we discuss elements of the students' authentic achievement, the impact of the learning environment on their design and problem-solving skills, and challenges they faced while working on their projects. Our analyses are organized by elements of authenticity in learning experiences. We report on evidence of authenticity of the students' learning experience and its impact on students' skills, challenges the students experienced throughout the course and differences between student teams.

5.3.1 Authenticity of the Learning Experience

Situating an introductory engineering design course in a making context provided students with a unique and rich learning experience that allowed them to explore various topics from different backgrounds. Through independent and collaborative learning activities, students practiced skills, learned new concepts and improved their level of expertise with a particular technology of interest to them. Team Mystique's making project exposed them to topics including programming, mechanical systems, computer-aided design (CAD) and the design of musical string instruments and electronics. Team Sunday Funday's project exposed them to mechanical systems. This experience allowed the students to learn about new concepts, strive for profound understanding of these concepts and communicate their ideas and conclusions by creating original physical objects.

The context and the activities that students were situated in helped them practice technical skills such as sketching, 3D modeling and printing, using CAD software, programming, designing PCBs and working with machining tools. These technical skills were not limited to the course's makerspace workshops, as students also had to learn to use extra digital and physical fabrication tools that could help them develop their prototypes. Moreover, throughout the course, students practiced concepts and skills they had learned in school. Students used software skills they had learned in previous courses to create sketches and build prototypes. Anna from Team Sunday Funday used her knowledge of mechanical elements design and CAD software from a course she took on mechanical design in the previous semester to make her designs. Dean from Team Mystique used his knowledge of C and Java Script programming languages to build software for his team's product.

We observed that making activities encouraged students to engage in collaborative and peer learning. Students in both teams worked together to research, brainstorm, discuss and sketch multiple concepts in the ideation phase. Team Mystique divided their final concept into subsystems and assigned each subsystem to a team member, although the students still helped each other design their respective subsystems. As students were designing their subsystems and making their prototypes, they had to consider the compatibility of their designs with their team members' designs. On the other hand, Team Sunday Funday worked collectively on their prototypes but didn't follow a particular work distribution system. Students often met during the week at a convenient time and worked on their project, often assigning tasks at their meetings.

> "Everyone has a system, and we are all kind of helping with each other's systems. It's not like we go off to the corner and do s***. We come back , and we brainstorm together, and we try to work as a group, and we try to talk about the input systems together a lot. A lot of that comes to me as well, since I am programming for the group, so everything has its inputs and outputs through the Arduino, except for the one cord component, so I have been doing a lot of throwing out ideas and trying to give the perspective of the programmer – what

> avenue they are going to take for their designs of the subsystems."
>
> – A conversation with Dean (Team Mystique) about his team's work distribution strategy.

Team members who were more experienced with the use of making technologies trained novice students to use tools in the makerspace and helped them with their designs. For example, students in Team Mystique taught each other 3D modeling in CAD, programming and electronics. Lisa and Dean helped Nora learn how to create a design in CAD software and 3D print an item. Dean also helped John with wiring electric motors. Students also often exchanged knowledge related to their engineering disciplines with other team members from different disciplines. Project managers – students who work at the makerspace and have taken the course before and demonstrated excellent leadership and technical skills – also helped students with information on creating their prototypes, such as knowledge about mechanical systems and configurations, options for materials and tools to use, and where the students could source the materials required to complete their prototype. They also helped students deal with the stress caused by approaching deadlines and moderated students' expectations of their final prototype. It should be noted that students felt they needed to have a physical item or a concept before they could reach out to their project manager for information or help.

The activities that students had to engage in to complete their making project allowed them to play multiple roles, as they had to participate in activities where they had to identify and think as interviewers when they met with their client, programmers, designers, leaders and team members, engineers and problem-solvers. Students also had multiple opportunities to demonstrate their ideas and artifacts to their peers, instructors and clients using sketches, CAD models, physical prototypes and presentations.

The values students assigned to their project work were not limited to academic success in the course. Students said they registered for the course because they considered would offer valuable experience for their career by providing them with real experience in design work and access to practical engineering activities where they have to "make" physical objects, not just create conceptual designs or solve traditional problems. Another value that students assigned to their project was the help they felt they were providing to their client by solving their problem. Team Mystique was motivated to share their design with others online so that it could be reproduced. For Team Mystique, completing the project and creating a guitar for their client – Nora's sister – had a personal value, as they were motivated to realize her dream; they felt they had raised her hopes and they had to deliver on their commitment to the extent that they pledged to work and improve their product after the end of the semester.

> Interviewer: "Why did you guys register for this course?"
>
> Oscar: "Because you choose between this course and [Engineering] Economics, and in this course, you learn a lot and you are helping someone at the same time, so it's a win-win."
>
> – A conversation with Oscar (Team Sunday Funday) about the reasons he registered for the course.

We observed that introducing making activities into this cornerstone design course and situating the course in a makerspace setting provided elements of the authentic learning environment framework [19]. First, making activities can help instructors construct authentic context and infuse authentic tasks into their curriculum. Second, making and learning in a makerspace environment is collaborative and offers students opportunities for mentorships and scaffolded learning. Making in a makerspace environment can also help instructors construct a learning environment for students with different levels of expertise, because making technologies offer makers multiple entry points to the technology. Third, making projects force students to adopt multiple perspectives to complete a project: students need to plan and organize tasks, source materials, communicate with individuals from different backgrounds, and encourage other students to share and articulate their ideas and designs with peers and the world. Fourth, a learning environment based on making activities offers instructors unlimited opportunities to adopt various authentic assessment techniques, such as client, peer and project manager evaluations.

5.3.2 Impact of the Authenticity of Experience

The making activities that students engaged in throughout the project allowed them to practice skills in a real engineering setting. We observed that students constructed meaning related to the engineering design process, problem-solving and teamwork.

5.3.3 Living the Design Process

The design problem that students in both teams were working to solve was an ill-defined problem of a real client with an accessibility need from the local community around the university. Students had to empathize with their client's needs to define a problem statement, listen to their client to understand their needs, and uncover design constraints elated to their client's requirements, their team budget, the time frame of the course, and their own technical abilities and expertise.

Students developed their concepts at the beginning stages of the project collaboratively, as each member in both teams developed their own sketches and ideas first before the members came together to consolidate their ideas to develop final concepts. Students in both teams then discussed their final concept with their client in their second client meeting. The ideation strategies that students used included research, benchmarking other existing solutions and ideas online, watching videos, talking with their client and consulting with their project managers. Students sketched their ideas and created a first prototype that was used as a demo to gain feedback on their ideas from their client, then later used to further develop their ideas. They continually redefined their conceptual design as they gained more understanding of the problem and their design constraints.

> Interviewer: "How did you guys come up with this concept?"
>
> John: "It was a variety of things. When we first heard of the project, we researched. We were studying videos of other things that people have come up with and read articles, and we said, 'OK, we can take some of that and adapt it for this particular situation.' Plus, our own ideas – such as the foot – were adapted from stuff we have seen from other projects that were not related. So, it was an amalgamation of a bunch of different things we have seen before."
>
> – A conversation with John (Team Mystique) about his conceptual design.

Prototyping was heavily present in students' discussions of their learning experience. Students constantly created prototypes to visualize and think about the details of their final prototype; to communicate ideas between each other or with the client; to understand how all the elements of their designs fit together; and to keep track of the elements of their designs and their specifications.

As students were going through the continuous process of refining their designs, they reflected on the importance of the conceptual design phase, considering the manufacturability of their designs and the evolutionary nature of design. At the final stages of the project, students noted that they had realized there was a relationship between the time and significance they awarded to their ideation and conceptual design phase and the number of iterations they had to go through later in the design process.

> Interviewer: "What are the lessons learned from last week?"
>
> Lisa: "To not look down on evolutionary design and just to always be flexible."
>
> . . .
>
> Interviewer: "When you say we should have done better planning , what would you have fixed?"
>
> Dean: "I think we could have seen some of the pivots that we had to make just by being a bit more proactive there, and I think this is a bit my fault as much as anyone if not more."
>
> Lisa: "I want to add to that. We were exceptionally haphazard with the design criteria and conceptual design deliverables. We were like, 'we know what we are doing we will make s*** up to make it look like we did research and stuff,' where really our research was for show and for the deliverable. I feel like we could have caught some of these issues if we had taken those two specific deliverables a little more seriously."
>
> – A conversation with team Mystique about their reflections on their design process.

The making nature of the project also exposed students to the ambiguity inherent in design thinking [8, 55]. Students indicated that at the beginning of the design process, sources of uncertainty came from missing information – either from their client or because they felt they lacked the knowledge to build a solution for their client's problem. The latter contributed to students' lack of confidence in their skillset to meet the client's needs at the beginning of the project and also increased students' feelings of uncertainty. At later stages of the design process, sources of uncertainty originated from sourcing materials to create prototypes and students' perception of their ability to meet design deadlines. Students coped with uncertainty by constantly seeking information, trusting each other and developing conceptual designs that could easily be modified to accommodate changes.

> "We don't have a lot of solid relevant skills and experience, and our uncertainty is really in 'can we physically execute this?' Who knows? Who knows if we will figure it out? But probably, yes."
>
> – Dean (Team Mystique) describing why he was feeling uncertain at the beginning of the project.

5.3.4 Solving an Authentic Problem

The learning experience helped students practice and improve their problem-solving skills by forcing them to encounter and solve unfamiliar problems. This helped them become more comfortable with taking risks and coping with ambiguity by actively defining the problem, seeking information, adapting to changes, managing stress and using subject knowledge to create solutions.

This approach of providing the students with the autonomy to define their problem, to frame their own project's scope and to constantly revise their concepts and designs – all while gathering feedback from their project manager and their client – increased students' confidence in their problem-solving skills. Engaging students in making activities to create a product that solves a client's real problem encouraged them to empathize with the user of their design, which helped them to define their problem, gather feedback and work to integrate it back into their designs. It also allowed students to improve their communications skills by learning to communicate their ideas with both technical and non-technical individuals. The interaction with a real client also motivated students to persist to complete their project and find a solution for their client's problem.

The nature of the making project also allowed students to develop and practice activities that are similar to those practiced by engineers – that is, activities that are complex and both technical and social. Students recognized that solving a problem is a process that requires research, creativity, iteration, teamwork, planning and reflection. Students conducted research throughout the course to explore existing solutions, set specifications, find answers to the smaller technical questions they were encountering, fill knowledge gaps, learn about the use of certain engineering tools, and search for materials that could be used to make their prototypes. They also constantly used sketching, digital and physical engineering tools to visualize concepts and create prototypes to present to their class, to their client and for their final Design Day presentation. We noticed that students with different levels of expertise had suitable entry points to technologies in the makerspace that allowed them to contribute to their team projects. For example, Nora had never built or tinkered with any 3D models, so she used TinkerCAD®, an entry-level browser-based platform for 3D modeling known for its simple interface, while Lisa, who had prior experience with 3D modeling and CAD, used the more advanced software Fusion360®. Both students were able to contribute to their team's project in a useful way. Other activities that students engaged in included preparing for meetings and presentations with the clients and the project manager, developing concepts and specifications, solving problems, planning, writing reports as part of the course's requirements, procuring supplies and navigating design constraints.

As students created their prototypes, they were constantly observing, testing and creating relationships between concepts they knew. They were also learning how to solve their client's problem. John, a second-year civil engineering student from Team Mystique, had to learn about simple electric motor systems to help his team build their second prototype. He researched types of motor systems and learned how to calculate the required power of the electric motor. As he learned about electric motors, he had to test his design and assess its suitability with other subsystems that his teammates were designing. Moreover, as students applied the concepts they were learning, they were constantly challenged to develop a deeper understanding of these concepts and domains of knowledge. Dean from Team Mystique initially thought he was going to use codes available on GitHub – an online software development tool – developed by other software developers and tweak them slightly to run his team's guitar. However, when he came to customize the code to his application, he realized there were too many computational libraries involved to run the code he had found on GitHub on his operating system, which in turn encouraged him to learn more about data transfer between an Arduino microprocessor and a Microsoft or Linux operating system.

Another observation was that students constantly reflected on their progress, the scope of their project, how they were managing their time and the learning environment, and how the course compared with other courses. Reflection was also a critical element in Team Sunday Funday's efforts to complete their project, as they fell behind in the design process and the course's deadline, and noticed they were not spending as much time working on their project due to other commitments and priorities. As a result of their reflection on their performance, they increased the time they were spending on the project, and one of the team members stepped up to assume leadership of the team. Member of Team Mystique reflected on their collective and individual performances: they reflected on their own progress against their team's project plan and the course's deadlines, each team member's weekly contribution, the technical problems facing the team, their performance in each of the design processes, and the evolution of their design from concept to final prototype.

5.3.5 Challenges

Although situating this cornerstone design course in a makerspace environment helped students improve many of their soft and technical skills, students still faced several challenges in this learning environment. These challenges can be classified in four categories: time management, stress, makerspace challenges, and challenges related to communications with the client. Table 1 shows the coding for the challenges that students faced throughout the course, together with the frequency of times a student or group of students raised the challenge, the number of students who experienced the challenge, and the number of interviews in which the challenges were discussed.

Students in both teams struggled with managing the time they had to complete their projects. Due to the multidisciplinary nature of the learning envir-

Table 1. Frequency of students' challenge themes that emerged from interviews with the students

Challenge code	Frequency	No. of students who experienced this challenge	No. of interviews out of 14
Time management	20	7	8
Stress	33	7	8
Makerspace challenges	11	7	5
Communication with the client	3	3	2

onment, students in each team were in different engineering disciplines and years of study, which meant that each had a different course program with different course loads. Some students were registered for six courses, while others were registered for four courses only. Therefore, in each team, each student ranked their project differently on their priority list. Some students had more time to dedicate to working on the project, while others were occupied with assignments and midterms in other courses. Most complaints came from students in the second-year civil engineering program about their struggle to find time to work on their project because they were occupied with requirements in other courses. Moreover, students in both teams thought the course load in this engineering design course was heavy.

Factors that delayed students in their iterative process of creating and improving their prototypes included the following: procurement of materials and parts to create their prototypes due to shipping delays or searching for a local supplier for a particular item; long wait times to use makerspace tools at the end of the semester, as many faculty of engineering students use the makerspace equipment and tools for other courses; and the need to "learn while making," as students had to learn new technical skills and concepts and solve unfamiliar problems before they could start creating or assembling an item.

Another challenge for students was experiencing high levels of stress. Students said they were stressed because they felt overwhelmed with the heavy workload of the project and other courses. They were also stressed about the uncertainty associated with solving engineering design problems, particularly finding information and resources to solve problems. Deadlines also caused students a lot stress, specifically the final deadline – students' presentation on Design Day. Iterations late in the prototyping phase also caused stress because students felt they were not going to be able to deliver a product for their client. Finally, meeting the client's expectations and having a functional prototype by Design Day were also sources of stress for the students. Table 2 presents the coding for each factor that contributed to students feeling stressed, together with the frequency of times a student or group of students raised the challenge, the number of students who experienced the challenge, and the number of interviews in which the challenges were discussed.

> "I am getting more afraid. I am feeling the time crunch, seeing the days count down. Doomsday is approaching. I think, at this point, my biggest fear is less something won't be ready for Design Day – because I am sure we can bring something out . . . to present. We are all competent people, and he [Dean] did sales all summer. The thing that I am more worried about is that if this isn't totally functional by Design Day, I am worried that we are all going to be too busy, too distracted, etc., to get this to a point where the client really wants, and we kind of got her hopes up a lot throughout this whole process. And I am worried that we are not going to present her with something that is what she wants. . . . And nothing is worse than letting down a child."
>
> – A conversation with Lisa (Team Mystique) about the reasons she is feeling stressed.

Situating the course in a makerspace also presented the students with several challenges, such as the limited operating hours of the makerspace, as students wanted to spend many hours working on their projects in the last two weeks of the semester but the makerspace had to close at 8 p.m. Students also faced logistical difficulties with sourcing materials and parts. As well, students faced difficulties with accessing the makerspace equipment and tools

Table 2. Frequency of factors that contributed to feelings of stress, as expressed in the interviews

Challenge code	Frequency	No. of students who experienced this challenge	No. of interviews out of 14
Workload	6	6	5
Uncertainties	3	4	3
Deadlines	9	7	6
Expectations	6	5	5

at the end of the semester, because the demand to use the makerspace's resources rose due to the increasing number of courses that had integrated the makerspace into their curriculum, which led to many of the faculty's students using the space for course work, in addition to ongoing personal projects.

Furthermore, students experienced challenges with communicating their ideas with their clients. Because the theme for course projects was accessibility, some clients had a disability that made communicating ideas with the client or gathering information and feedback from the client challenging and required the presence of a third party who had a close relationship with the client to facilitate the communication process.

5.3.6 *Differences Between Teams*

Throughout the study, we observed several differences between the two teams in how they executed their projects. These differences were present in students' motivation towards the project, in strategies used in each of the project's design phases, in team dynamics and in time management.

The project selection process for each team was different, since Team Mystique had proposed their own client and had a personal connection to the client's problem, while Team Sunday Funday selected their project from a list proposed by the course's instruction team. The difference in how each team selected their project affected the level of motivation for the project. Team Mystique felt very motivated to solve their client's problem and expressed interest in continuing to work on their prototype after the semester, going so far as to post their design online in the hopes that it would be improved by a wider community of designers. On the other hand, Team Sunday Funday didn't express interest in continuing to work on the project after the semester and indicated that their project wasn't high on their priority list because they had other courses in their engineering program that needed their attention. Another factor that detracted from Team Sunday Funday's interest in continuing to work on the project after the semester was that they thought there were already available products in the market that might solve the client's problem.

Through the design phases, each team adopted different work strategies. During the conceptual design phase, Team Mystique developed one concept that was ambitious and didn't consider the design constraints of the project, while Team Sunday Funday developed two concepts to present to their client. During the prototyping phase, Team Mystique developed several prototypes and communicated with their client frequently. Each member of Team Mystique was responsible for developing their own prototype for the subsystem they were responsible for, while Team Sunday Funday started the prototyping phase later in the course due to their focused attention on other courses.

These differences in how each team completed their project were also a product of differences in the dynamics of each team and how they managed their project and time. Team Mystique selected a leader by the second week of the course and developed a project plan that had more aggressive deadlines than the course's deadlines. The leader, Dean, was a third-year software engineering student whose role included helping everyone with their designs, assigning tasks to each team member, following the team's progress and designing his own subsystem. Conversely, Team Sunday Funday did not pick a leader or follow a plan to complete their project. Midway through the project, as students were struggling to create their prototypes, one student naturally emerged as the leader and started organizing the team's tasks. The students in Team Sunday Funday also struggled with breaking down tasks into smaller ones and with prioritizing their tasks. It should be noted that all of the students in Team Sunday Funday were from the second-year program, and this might have been a factor in them not assigning a leader for their team.

6. Discussion

We discuss the implications of the findings of this study for understanding how integrating a making program into an introductory engineering design course can create the conditions for an authentic learning environment. We also discuss the implications of our findings for the design of authentic learning environments for teaching engineering design.

6.1 *Authenticity of the Learning Experience*

Authenticity of the learning environment is discussed in engineering education literature in four main categories: context authenticity, task authenticity, impact authenticity and personal/value authenticity [56]. Ethnographic studies on professional engineers have defined engineering design as a social process that goes beyond the work of a creative engineer at a workstation to include many stakeholders, such as production and marketing personnel, purchasing and finance professionals, clients and contractors [57, 55]. Through the making experience in this course, students had to participate in activities where they had to communicate with the user of their product to understand their needs and define their problem. They also had to draft a budget for their project and secure an approval from their project manager, procure materials and parts from suppliers independently, create multiple prototypes, plan schedules and milestones, and distribute tasks among each other. These activities exposed students to a learning experience where their work was not limited to technical activities such as drafting technical drawings and reports; rather, their work extended to multiple organizational activities of ongoing reconciliation, persuasion, negotiation and management [58, 59].

Students' realization of the importance of the problem definition phase and conceptual design phase to the success of their design project was an indication of their progression from novice designers to more experienced ones. Throughout the course, students in both teams continued to gather information and redefine their problem and scope of work. Both of these observations point to similarities with expert performances in engineering design [60]. Moreover, we noticed that situating students in a learning environment with authentic tasks and contexts gave them an opportunity to spend hours practicing their skills and reflecting on their work and what they were learning, something that in turn helps students proceed towards more advanced performance.

For Team Mystique, the object of design itself heavily influenced the structure of the design process and the division of labor within the team. The product was divided into multiple subsystems, which were allocated to team members depending on each members' expertise, engineering discipline and learning objectives. This allowed each student to take accountability for their own design process while working collectively with the other team members to make sure all the systems were compatible. The outcome of the student's authority over their design process was a noticeable high level of motivation and enjoyment of the learning experience and the project work. In Team Mystique, each student came up with a brand name for their system, and they all agreed on a product name. For Team Sunday Funday, the delay they experienced in meeting their deadlines, especially at the beginning of the project, was partly due to their failure to break down their product into smaller systems, organize tasks accordingly and distribute tasks between the team members.

The multidisciplinary nature of the making projects and of the student teams meant that students were exposed to different worlds of technical specializations and, therefore, to knowledge, modes of thinking, dialects, metaphors, instruments and crafts beyond their engineering discipline in order to solve their client's problem. Moreover, similar to how engineers progress from novices to professional engineers through peripheral participation (by first participating in simpler tasks, guided by senior colleagues) in the workplace [61], first-year students and novice makers were guided by students with more experience with making technologies, by senior students and by project managers in the use of equipment and tools in the makerspace, in scaffolded learning of 3D modeling and CAD, and in learning engineering concepts that were new to them.

The making projects also challenged students with three main types of design constraints: human constraints, such as the client's needs and ability to communicate them with the students; technical constraints, such as those faced by John while designing and selecting electric motors for his subsystems and by Dean as he was designing software to be compatible with his teammates' subsystems; and cost constraints, such as those experienced by both teams as they chose between options and trade-offs for their designs. Moreover, as students were making their prototypes, they realized these constraints can often be solved through negotiation. Given that Team Mystique had to create multiple iterations of their designs through the course of the project, they ran out of budget and had to negotiate with the course instructor for extra funding for their project. This is a true characterization of engineering design constraints: although they might be numerous and wide-ranging, they are constantly reconstructed [57, 62].

Students also engaged in authentic design tasks when they used sketches and prototypes to communicate ideas, gain understanding and solve problems. Studies on professional engineering practices describe the way engineers use sketches on both paper and CAD interfaces to grapple with ideas and communicate with others [58]. Students in both teams used hand sketches to develop initial conceptual designs and moved to using CAD models, 3D printed physical prototypes or models made out of cardboard to visualize their designs, solve problems they were facing during the design process, figure out how elements of their design fit together, visualize modifications to their design, and communicate ideas with their client and project manager and gather feedback from them. The availability of 3D printers and other rapid prototyping equipment in the makerspace empowered students to transform their designs to three-dimensional reality in a matter of hours after creating them on CAD software [63], allowing students to progress quickly on the design of their final product. The introduction of making activities into the engineering curriculum therefore also contributes to preparing engineering students for changes in the engineering profession stemming from the use of new technologies in engineering work, such as the increasing use of computational technologies [58] and the increasing use of rapid prototyping technologies, which have a strong impact on productivity by accelerating product development [64–66].

Another observation about the making projects that students had to complete is that they resembled workplace projects in the sense that they were ill-structured and complex. Also, they had multiple possible solutions, vague constraints that included non-technical constraints, distributed knowledge and unclear goals [61]. Students were challenged with a product design problem where they had to work both independently and collectively to direct and monitor their own learning and identify the knowledge they needed to solve the problem and make their final prototype. Based on this learning environment, it is our observation that the maker movement has the potential to connect and prepare engineers of the future to work with and for constituents rather than corporations on some of the planet's biggest problems, including climate change, sustainable energy and famine [58].

The making projects gave students of a glimpse of the impact that the engineering profession has on society. We also observed that learning projects that offer personal and value authenticity, as in the case of Team Mystique, provided more opportunities and motivation for learning, because students were motivated to complete their project primarily to improve their client's quality of life. Our observation is in line with the argument from Wang et al. [56] that projects that are close to the students' own life, answer personal questions that the students' have, or satisfy the students' or their community's needs deliver authentic education most effectively.

6.2 Implications for the Creation of Authentic Learning Environments for Engineering Design

We found that the making nature of the projects entailed important elements that are necessary to construct an authentic learning environment for engineering design, such as access to the interdisciplinary and multidisciplinary nature of engineering design, as well as engagement in social and organizational activities that are the core of engineering design and offer an adequate level of ambiguity to familiarize students with navigating design problems as future engineers.

Jeff Herrington's [19] framework for designing authentic learning environments outlines nine elements that are necessary in any authentic learning environment: authentic context, authentic tasks, access to expert performances, access to multiple roles and perspectives, collaborative learning, reflection, articulation, scaffolding and authentic assessment. Our findings lead us to elaborate on a few of these elements to help engineering educators construct authentic engineering design learning experiences.

First, an authentic engineering design context must provide students with an ill-defined design problem with unclear constraints that can help students familiarize themselves with the inherent ambiguity feature of engineering design projects. Moreover, the presence of a real client, an object of design, the possibility for multiple solutions and the students' authority to decide on the learning path they want to follow to reach a solution are all essential for fostering an authentic engineering design context for the learning environment.

Second, the tasks that students participate in should not be limited to technical activities. Rather, they should extend to other organizational activities, such as breaking down a project into smaller tasks and distributing the workload among team members.

Third, to facilitate effective collaborative learning, there should be a clear distribution of roles among the student team members. This can be achieved easily if there is diversity in the level of expertise and backgrounds within the team. In a previous study we conducted to compare the impact of team formation methods on student achievement, we found that the choice of team formation method – self-assignment or instructor assignment – did not have an impact on student academic achievement in the course [67]. Therefore, we recommend that instructors form student teams keeping diversity of expertise and background in mind.

A new element that we perceived as essential to constructing an authentic engineering design learning and that is a characteristic of making activities is access to interdisciplinary and multidisciplinary learning opportunities [44, 68]. Given that design is a social activity that includes multiple participants – each with different technical backgrounds that have distinct language and instruments – authentic learning environments must introduce students to this intrinsic feature of engineering design [57]. Moreover, the learning environment should provide opportunities where students can explore the roles of many stakeholders involved in an engineering design project, such as project managers, suppliers, contractors, clients and investors.

6.3 Stress as a Main Challenge

One of the main challenges facing students in this learning environment was constantly feeling stressed. The relationship between stress and a designer's creativity is complex. Low-stress-inducing situations have been found to contribute to increases in creative performance, while high-stress-inducing situations contribute to decreases in creativity; moreover, contexts that are characterized as uncontrollable decrease creative performance [69]. Also, mental effort at low and medium stress levels is stronger than mental effort at higher stress levels [70]. Sources of stress in the course under study can be classified into two main groups: sources related to workload and sources related to the students' perception of their ability to provide a useful prototype to their client. Nguyen & Zeng [37, p. 76] argued that students' stress is positively related to workload and negatively related to mental capacity – workload being defined as tasks assigned to a student, and mental capacity being defined as students' own knowledge and skills required to complete the tasks assigned to them. How students react to their workload differs from one student to another and depends on each student's particular circumstances; similarly, since learning within a making context involves an array of different topics and multiple participants with different backgrounds, different skills and varying levels of expertise, student stress levels will vary.

Byron, Khazanchi, and Nazarian [69] found that some stress is necessary to induce creativity. But for learning environments where making is central, ensuring that students have a sense of control over their workload and their mental capacity is vital to ensuring that students go through a positive learning experience where stress does not hinder their creativity. Although the course in this study used scaffolding strategies to help students develop the skills required to complete their prototypes, more consideration should be given to the workload in such a learning environment and to balancing that workload with students' workload in other courses.

6.4 Authentic Achievement in Engineering Design Courses

Student achievement in this authentic engineering design learning experience depended on several factors that expanded beyond the standards for authentic achievement of Wehlage, Newmann and Secada: construction of new knowledge, disciplined inquiry and value beyond school [31]. We observed that students' capability to deconstruct the design project into smaller subsystems and to further break down tasks was essential to their progress and success. Also, their ability to plan, organize and prioritize tasks was essential to their ability to meet deadlines. Moreover, students' ability to distribute tasks and roles among one another and assign a leader to the team who could take the lead on managing the project and help organize tasks was crucial to their achievement and enjoyment of their learning experience. Furthermore, their ability to manage their time on the project and to manage their time between this cornerstone design course with its making activities and other academic commitments was vital for them to be able manage their stress level and enjoy their project work.

These observations lead us to argue that a new element should be added to the disciplinary inquiry element of the conceptualization of authentic achievement. Wehlage, Newmann and Secada [31] defined disciplined inquiry as cognitive work that relies on the use of a prior knowledge base, strives for in-depth understanding of the subject knowledge and communicates ideas and thoughts in an elaborate manner. This definition fails to capture the social and organizational nature of the design process. For students to accomplish an authentic achievement in engineering design, they have to learn to navigate the uncertainty of the social and organizational facets of the design process. In an authentic engineering design learning environment, students have to demonstrate an ability to organize, plan and prioritize activities in a multidisciplinary design project.

6.5 Implications for Integrating Making Activities into Engineering Design Courses

Our findings suggest several implications for engineering design instructors who might be interested in incorporating making projects into their curriculum. First, we note that the presence of a leader and a work distribution structure between the team members played a vital role in students' authentic achievement. Although a leader did emerge eventually for Team Sunday Funday, the presence of a leader from the start of Team Mystique's design process helped them to achieve their learning goals and better manage their time and project. The presence of an obvious leader in Team Mystique can be attributed to many factors, including the diversity in engineering disciplines among team members, years of study spent in engineering school and the familiarity of the team members. We think ensuring a diverse team in terms of both disciplinary knowledge and level of expertise would ensure peer learning and mentorship and a better distribution of roles among team members.

Second, proper scaffolding in time and project management that is situated as part of the functions of the authentic activity should be offered to students to ensure that they capitalize on the learning opportunities of the making activities and to support an authentic engineering design experience. Also, encouraging students to start their design process as early in the semester as possible and to spend adequate time in the ideation and conceptual design phases would give them adequate time for their prototyping phases.

Third, in a multidisciplinary learning environment with participants from different engineering disciplines and years of study, instructors should consider the students' workload and emphasize the importance of their learning over delivering a final functional prototype. Even though the product of the design in design courses is important, so too is learning the various skills, such as teamwork, communications, problem-solving and the ability to follow a design methodology [72]. In students' discussions of the challenges they were facing, they emphasized the product and sense of accountability to the client as a source of stress. While this can be seen as an advantage of incorporating making projects into engineering design courses – because it situates students in a more authentic situation than that of capstone design courses where students still recognize the instructor as the ultimate final authority in the learning environment [73] and because time is a limited resource within a semester-long course – instructors should communicate and stress the importance of the students learning critical skills over delivering a functional final prototype, as this would help regulate students' stress and help them focus and reflect on their learning.

Fourth, during our discussions with the students about recommended improvements for the course, they indicated they were interested in and enjoyed learning practical skills. We recommend that instructors expose students to as many making technologies as possible and that this exposure be situated in an authentic context. This would motivate student to learn and train them to use different tools to create their prototypes, thus reducing the demand for 3D printers.

7. Conclusion

In this article, we described students' learning experiences in an engineering design course that was situated in a makerspace environment and had making activities as a central theme. We found that the integration of making activities into engineering design courses offers students an authentic design experience that exposes them to a diverse set of topics and increases their confidence in their design and problem-solving skills. Making activities also give students opportunities to perform in ways similar to what will be expected of them as professionals. The integration of making activities also has the potential to steer undergraduate engineering curricula to offer more contemporary images of the engineering profession that is creative, collaborative and more oriented towards agendas of social good.

References

1. E. Wenger-Trayner, M. Fenton-O'Creevy, S. Hutchison, C. Kubiak and B. Wenger-Trayner, *Learning in Landscapes of Practice: Boundaries, identity, and knowledgeability in practice-based learning*, Routledge, New York, 2015.
2. National Academy of Engineering, *The Engineer of 2020*, National Academies Press, Washington, DC, 2004.
3. National Intelligence Council, *Global Trends 2025: A Transformed World*, Washington, DC, 2008.
4. C. Baillie, Enhancing creativity in engineering students, *Engineering Science and Education Journal*, **11**(5), pp. 185–192, 2002.
5. National Intelligence Council, *Global Trends. Paradox of Progress*, Washington, DC, 2017.
6. L. Jamieson and J. Lohmann, *Creating a Culture for Scholarly and Systematic Innovation in Engineering Education. Phase 1 Report*, American Society of Engineering Education, Washington, DC, 2009.
7. G. Tryggvason and D. Apelian, Re-engineering engineering education for the challenges of the 21st century, *IEEE Engineering Management Review*, **37**(1), 2009, p. 38.
8. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, Engineering Design Thinking, Teaching, and Learning, *Journal of Engineering Education*, **94**(1), pp. 103–120, 2005.
9. K. A. Smith, S. D. Sheppard, D. W. Johnson, and R. T. Johnson, Pedagogies of Engagement: Classroom-Based Practices, *Journal of Engineering Education*, **94**(1), pp. 87–101, 2005.
10. Z. Siddique, P. Hardré, A. Bradshaw, M. Saha and F. Mistree, Fostering innovation through experiential learning, *Proceedings of the ASME Design Engineering Technical Conference*, **6**, pp. 791–803, 2010.
11. T. A. Litzinger, L. R. Lattuca, R. Hadgraft and W. Newstetter, Engineering education and the development of expertise, *Journal of Engineering Education*, **100**(1), pp. 123–150, 2011.
12. A. Coble, A. Smallbone, A. Bhave, R. Watson, A. Braumann and M. Kraft, Delivering authentic experiences for engineering students and professionals through e-labs, *IEEE Education Engineering Conference (EDUCON)*, April 14–16, pp. 1085–1090, 2010.
13. M. Lande, Student Learning Trajectories from Making and Engineering Activities, *American Society of Engineering Education Annual Conference*, 2018.
14. S. Papavlasopoulou, M. N. Giannakos and L. Jaccheri, Empirical Studies on the Maker Movement, a promising approach to learning: A literature review, *Entertainment Computing*, pp. 57–78, September, 2016.
15. J. Castek, M. Schira Hagerman and R. Woodard, Principles for Equity-centered Design of STEAM Learning-through-Making, University of Arizona, Tucson, 2019.
16. S. Vossoughi and B. Bevan, *Making and Tinkering: A Review of the Literature*, National Research Council Committee on Successful Out-of-School STEM Learning, Washington, DC, pp. 1–55, 2014.
17. R. C. Smith, O. S. Iversen and M. Hjorth, Design thinking for digital fabrication in education, *International Journal of Child-Computer Interaction*, 5, November 2015.
18. B. Bevan, The promise and the promises of Making in science education, *Studies in Science Education*, **53**(1), pp. 75–103, 2017.

19. J. Herrington, Introduction to Authentic Learning, in *Activity Theory, Authentic Learning and Emerging Technologies*, V. Bozalek, D. Ng'ambi, D. Wood, J. Herrington, J. Hardman, and A. Amory (eds), Routledge, London, pp. 61–67, 2014.
20. J. Herrington and R. Oliver, An instructional design framework for authentic learning environments, *Education Technology Research and Development*, **48**(3), pp. 23–48, 2000.
21. J. Herrington, T. C. Reeves and R. Oliver, Authentic Learning Environments, in *Handbook of Research on Educational Communications and Technology*, Springer, New York, pp. 401–412, 2014.
22. J. S. Brown, A. Collins and P. Duguid, Situated cognition and the culture of learning, *Educational Researcher*, **18**(1), pp. 32–42, 1989.
23. J. Lave and E. Wenger, *Situated Learning: Legitimate Peripheral Participation*, Cambridge University Press, Cambridge and New York, 1991.
24. P. Boghossian, Behaviorism, constructivism, and socratic pedagogy, *Educational Philosophy and Theory*, **38**(6), pp. 713–722, 2006.
25. P. Berger and T. Luckmann, *The Social Construction of Reality: Treatise in the Sociology of Knowledge*, Penguin Books, New York, 1966.
26. F. Blackler, Knowledge, Knowledge Work and Organizations: An Overview and Interpretation, *Organization Studies*, **16**(6), pp. 1021–1046, 1995.
27. J. Lave, Teaching, as learning, in practice, *Mind, Culture, and Activity*, **3**(3), pp. 149–164, 1996.
28. B. M. M. Lombardi and D. G. Oblinger, *Authentic Learning for the 21st Century: An Overview*, Educause Learning Initiative, Boulder, CO, May 2007.
29. R. B. Iucu and E. Marin, Authentic Learning in Adult Education, *Procedia-Social and Behavioral Sciences*, **142**, pp. 41–415, 2014.
30. F. M. Newmann & Associates, *Authentic Achievement: Restructuring Schools for Intellectual Quality*, Jossey-Bass Inc., San Franscisco, 1996.
31. G. Wehlage, F. M. Newmann and W. G. Secada, Standards for Authentic Achievement and Pedagogy, in F. M. Newman & Associates (eds), *Authentic Achievement: Restructuring Schools for Intellectual Quality*, Joessy-Bass Inc., San Francisco, 1996.
32. M. Grubbs and G. Strimel, Engineering Design: The Great Integrator, *Journal of STEM Teacher Education*, **50**(1), pp. 77–90, 2015.
33. A. F. McKenna and P. Hirsch, Evaluating student confidence in engineering design, teamwork and communication, *ASEE Annual Conference & Exposition, Conference Proceedings*, pp. 5911–5921, 2005.
34. V. Wilczynski, J. Zinter and L. Wilen, Teaching engineering design in an academic makerspace: Blending theory and practice to solve client-based problems, *ASEE Annual Conference & Exposition, Conference Proceedings*, 2016.
35. L. Martinez, P. Sullivan and E. Pines, Integration of Engineering Capstone within a Makerspace Environment, *ASEE Annual Conference & Exposition, Conference Proceedings*, 2017.
36. A. Longo, B. Yoder, R. C. C. Guerra and R. Tsanov, University makerspaces: Characteristics and impact on student success in engineering and engineering technology education, *ASEE Annual Conference & Exposition, Conference Proceedings*, 2017.
37. S. Papert and I. Harel, Situating Constructionism, in I. Harel and S. Papert (eds), *Constructionism*, Praeger Publishers, 1991.
38. J. Cohen, W. M. Jones, S. Smith and B. Calandra, Makification: Towards a Framework for Leveraging the Maker Movement in Formal Education, *Proceedings of Society for Information Technology & Teacher Education International Conference*, (1), pp. 129–135, 2016.
39. L. Martin, The Promise of the Maker Movement for Education, *Journal of Pre-College Engineering Education Research*, **5**(1), pp. 30–39, 2015.
40. M. S. Sheppard, S. S. Jordan, M. Lande and A. F. McKenna, Exploring Making-based Pedagogy in Undergraduate Mezzanine-level Engineering Courses: American Society for Engineering Education, *American Society of Engineering Education Annual Conference*, 2018.
41. A. Hodges and Y. M. Al Hamidi, Improving Students' Writing Skills by Integrating Prototyping Activities in their Writing Course, *American Society of Engineering Education Annual Conference*, 2018.
42. V. Wilczynski, A Classification System for Higher Education Makerspaces: American Society for Engineering Education, *ASEE Annual Conference & Exposition, Conference Proceedings*, 2017.
43. P. Blikstein, Z. Kabayadondo, A. Martin, and D. Fields, An Assessment Instrument of Technological Literacies in Makerspaces and FabLabs, *Journal of Engineering Education*, **106**(1), pp. 149–175, 2017.
44. L. Brahms and K. Crowley, Making Sense of Making: Defining Learning Practices in MAKE Magazine1, in K. Pepler, E. Halverson, and Y. Kafai (eds), *Makeology: Makers as Learners*, 2016, pp. 13–28.
45. K. Sheridan, E. R. Halverson, B. K. Litts, L. Brahms, L. Jacobs-Priebe and T. Owens, Learning in the Making: A Comparative Case Study of Three Makerspaces, *Harvard Educational Review*, **84**(4), Winter, pp. 505–531, 2014.
46. D. M. Mertens, *Research and Evaluation in Education and Psychology: Integrating Diversity With Quantitative, Qualitative, and Mixed Methods*, 2nd ed., Sage Publications, Thousand Oaks, CA, 2005.
47. A. J. Onwuegbuzie and N. L. Leech, A call for qualitative power analyses, *Quality & Quantity*, **41**(1), pp. 105–121, 2007.
48. K. Charmaz and L. L. Belgrave, Qualitative interviewing and grounded theory analysis, in J. F. Gubrium, J. A. Holstein, A. B. Marvasti, K. D. McKinney (eds), *The SAGE Handbook of Interview Research: The Complexity of the Craft*, SAGE Publications, Inc., Thousand Oaks, CA, pp. 347–366, 2012.
49. A. J. Onwuegbuzie and N. L. Leech, Sampling Designs in Qualitative Research: Making the Sampling Process More Public, *The Qualitative Report*, **12**(2), pp. 238–254, 2007.
50. A. K. Shenton, Strategies for ensuring trustworthiness in qualitative research projects, *Education for Information*, **22**(2), pp. 63–75, July 2004.
51. K. Charmaz, *Constructing Grounded Theory: A Practical Guide Through Qualitative Research*, Sage Publications Ltd, London, 2006.
52. M. B. Miles and A. M. Huberman, *Qualitative Data Analysis*. Thousand Oaks: SAGE, 1994.
53. E. Namey, G. Guest, L. Thairu and L. Johnson, Data reduction techniques for large qualitative data sets, in G. Buest and K. MacQueen (eds), *Handbook for Team-based Qualitative Research*, AltaMira Press, Lanham, MD, 2008.
54. J. Saldaña, *The Coding Manual for Qualitative Researchers*, *Second Edition*. Sage Publications, Thousand Oaks, CA, 2013.
55. C. J. Atman, D. Kilgore and A. McKenna, Characterizing design learning: A mixed-methods study of engineering designers' use of language, *Journal of Engineering Education*, **97**(3), pp. 309–326, 2008.

56. J. Wang, M. Dyehouse, N. R. Weber and J. Strobel, Conceptualizing Authenticity in Engineering Education: A Systematic Literature Review, *ASEE Annual Conference & Exposition, Conference Proceedings*, 2012.
57. L. L. Bucciarelli, An ethnographic perspective on engineering design, *Design Studies*, **9**(3), pp. 159–168, 1988.
58. R. Stevens, A. Johri, and K. O'Connor, Professional engineering work, in A. Johri and B. M. Olds (eds), *Cambridge Handbook of Engineering Education Research*, 2015.
59. L. Suchman, Organizing Alignment: A Case of Bridge-building, *Organization*, **7**(2), pp. 311–327, 2000.
60. C. J. Atman, R. S. Adams, M. E. Cardella, J. Turns, S. Mosborg and J. Saleem, Engineering design processes: A comparison of students and expert practitioners, *Journal of Engineering Education*, 2007.
61. D. Jonassen, J. Strobel and C. B. Lee, Everyday problem solving in engineering: Lessons for engineering educators, *Journal of Engineering Education*, **96**(4), pp. 359–379, 2007.
62. D. L. Kleinman, Everyday Engineering: An Ethnography of Design and Innovation (review), *Technology and Culture*, **45**(4), pp. 849–850, 2004.
63. J. E. De Leon and G. E. Winek, Incorporating Rapid Prototyping Into the Engineering Design Curriculum, *Engineering Design Graphics Journal*, **64**(1), pp. 18–23, Winter 2000.
64. A. K. Kamrani and E. A. Nasr, Rapid Prototyping, in A. K. Kamrani and E. A. Nasr (eds), *Engineering Design and Rapid Prototyping*, Springer, New York, 2010.
65. A. Ahmad, M. I. Mazhar and I. Howard, A framework for the adoption of rapid prototyping for SMEs: From strategic to operational, *International Journal of Industrial Engineering: Theory Applications and Practice*, **19**(3), 2012.
66. M. Srivastava, S. Maheshwari, T. K. Kundra and S. Rathee, Estimation of the effect of process parameters on build time and model material volume for fdm process optimization by response surface methodology and grey relational analysis, in L. J. Kumar, P. M. Pandey, and D. I. Wimpenny (eds), *Advances in 3D Printing and Additive Manufacturing Technologies*, Springer, New York, pp. 29–38, 2016.
67. M. Galaleldin, J. Boudreau and H. Anis, Team Formation in Engineering Design Courses, *Conference: Proceedings 2019 Canadian Engineering Education Association*, 2019.
68. G. S. Stager, Papert's Prison FabLab: Implications for the maker movement and education design, *Proceedings of the 12th International Conference on Interaction Design and Children (IDC '13)*, pp. 487–490, 2013.
69. K. Byron, S. Khazanchi and D. Nazarian, The relationship between stressors and creativity: A meta-analysis examining competing theoretical models, *Journal of Applied Psychology*, **95**(1), pp. 201–212, 2010.
70. T. A. Nguyen and Y. Zeng, A physiological study of relationship between designer's mental effort and mental stress during conceptual design, *Computer-Aided Design*, **54**(C), pp. 3–18, 2014.
71. Y. Zeng, A Theoretical Model of Design Creativity: Nonlinear Design Dynamics and Mental Stress-Creativity Relation, *Journal of Integrated Design Process Science*, **16**(3), pp. 65–88, 2012.
72. M. Paretti, R. Layton, S. Laguette and G. Speegle, Managing and mentoring capstone design teams: Considerations and practices for faculty, *International Journal of Engineering Education*, **27**(6), pp. 1192–1205, 2011.
73. D. P. Dannels, Teaching and Learning Design Presentations in Engineering: Contradictions between Academic and Workplace Activity Systems, *Journal of Business and Technical Communication*, pp. 139–169, 2003.

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