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Development of Student Comfort with Various Fabrication Methods in Aerospace and Mechanical Engineering Design Curriculum

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Tyler C. Kreipke, CSC, PhD, Kerry L. Meyers, PhD

Abstract

Student self-efficacy, or a student's belief in their ability to perform particular tasks, positively contributes to a number of beneficial student characteristics. The development of student-perceived competence with engineering processes should, therefore, serve as a fundamental goal for engineering curricula. This study seeks to provide further insight into what types of activities contribute to the development of student self-efficacy towards common fabrication methods in aerospace and mechanical engineering, particularly exploring potential differences between the effects of shorter practical assignments and longer design projects. Undergraduate engineering students enrolled in 3 different 200-level design courses in the aerospace and mechanical engineering department at a medium-sized, Midwestern, private university were asked to participate in a survey characterizing their comfort level with and prior exposure to various fabrication methods. The fabrication methods analyzed in this study included additive manufacturing (e.g. 3D printing), basic fabrication methods (e.g. hand tools, drill presses), advanced fabrication methods (e.g. CNC mills/routers, water-jet cutters), and 3D modeling (e.g. SolidWorks). Throughout the semester, students were introduced to these topics in the 3 courses via lectures, short practical, or "hands-on", assignments that had the students use or perform various fabrication processes, and multi-week design projects. The survey was administered at 3 or 4 different timepoints throughout the semester, dependent upon the course. Appropriate data collection timepoints for each course were determined as coming after the completion of course-specific milestones that exposed students to the different fabrication methods. Aggregate and course-specific data from the survey were used to assess how student comfort with relevant fabrication methods changed throughout the semester. Effects of prior outside exposure to these fabrication methods and gender were also explored. Results showed that student comfort level with each fabrication method generally increased throughout the semester in the 3 courses in response to different assignment types. The greatest increases in comfort were seen from projects that required students to engage with fabrication methods to which they had little previous exposure. In some cases, the comfort levels developed from shorter practical assignments were not statistically different than those from multi-week projects. This study suggests that lectures may be a good introduction to increase student comfort/confidence with some fabrication methods, but students/curricula can benefit even more from the incorporation of experiential and project-based learning activities that require the use of various fabrication methods, such as shorter practical assignments and multi-week integrative projects, respectively.

1. Introduction

1.1. Self-Efficacy

Self-efficacy in students describes their perception of their abilities to perform particular tasks [1], and has been found to positively correlate with a number of desirable student outcomes. These include academic performance according to traditional metrics, such as achievement scores and cumulative GPA [2],[3]. More importantly, self-efficacy has been found to be beneficial not only to task-specific content within classroom settings, but to the learning process itself, and to a number of other more qualitative student characteristics [4]. Self-efficacy is strongly related to motivation and cognitive engagement with course material [5]. It contributes to resilience, greater effort exerted in problem-solving, and persevering in challenges [4]. With higher self-efficacy, students are more likely to employ a wider range of useful cognitive and metacognitive strategies in solving problems, contributing to greater academic performance [4],[5]. This persistence associated with self-efficacy has been seen to apply not only to acute challenges, but also correlates with longer-term phenomena, such as student retention within particular majors [3]. This reflects an influence of self-efficacy on career choice. Self-efficacy can influence students at the beginning of their studies in selecting their major and at the completion of their studies by increasing their perceived career options [6]. Finally, self-efficacy is also associated with better mental health in students, specifically seen in reduced anxiety levels in students with higher self-efficacy [7].

Clearly, the beneficial practices and traits associated with self-efficacy indicate it as a desired characteristic in students. However, self-efficacy is not simply a static personal attribute that should be selected for in admissions processes. It is, rather, a dynamic quality, the cultivation of which should be a central aim of engineering education [4],[8],[9],[10]. Current conceptual models suggest four key components as primary contributors to self-efficacy: (1) mastery experiences (e.g. previous experiences that developed/showed competence for a particular task), (2) vicarious experiences (e.g. seeing someone that a student views as similar to herself/himself succeeding in similar tasks), (3) social persuasion (e.g. affirmation of a student's abilities), and (4) emotional factors associated with a particular task (e.g. anxiety or confidence) [2]. While all of these factors can be helpful for developing self-efficacy in students, some are more within an instructor's control than others. Particularly, instructors have greater control over their ability to provide opportunities for mastery experiences in the design of their courses, as well as social persuasion by affirming students' displays of competence through proper feedback. In addition, it is important to note that some of these areas relate more strongly to academic performance than others. Previous mastery experiences have been found to have the strongest correlation with academic achievement when compared to the other sources of self-efficacy [2]. This suggests that focusing on ways to provide opportunities for exposure to and mastery of concepts/tasks in engineering may be a particularly effective means of cultivating self-efficacy in students. These experiences can in turn lead to improved performance in subsequent engineering contexts. This also suggests that exposure and mastery experiences may be especially beneficial in early courses within engineering curricula. Particular types of active learning can provide an apt avenue for cultivating these exposure and mastery experiences.

1.2. Active Learning Styles – Experiential and Project-Based Learning

Active learning, as the name implies, actively engages students in the learning process, rather than allowing for passive reception of material. Active learning has long been noted as an effective means for developing conceptual understanding. This learning/teaching style has been increasingly incorporated into engineering classes through the use of practica and projects [11],[12],[13]. These assignments provide opportunities for students to more fully engage course material, leading to a range of beneficial learning outcomes. Active learning has been found to lead to improved academic performance in both the retention and application of material [10],[14],[15]. In one study [15], instructors saw that reinforcing audio-visual lectures with an active laboratory exercise for additive manufacturing improved not only the technical performance of groups in a bracket design challenge, but also their creativity in designing a solution. In addition to improving objective academic performance, the incorporation of active learning has been found to improve student experience and self-efficacy [11],[16]. Studies have shown that the integration of practical design/technical activities within a course have led to higher student satisfaction with and improved perception of the course [10],[12],[13]. This has also correlated with greater student motivation and engagement with coursework [14],[16]. In an analysis of training for technical procedures in the medical field, Clanton et al. [17] have proposed that the incorporation of practica contributes to a positive feedback loop of content engagement: hands-on training increases student confidence, which increases their likelihood/willingness to use these skills, providing further practice, and further increasing confidence. Similar dynamics may hold in engineering, as a study by Gillespie and Nossoni [18] indicated that introducing students to fabrication methods and resources in a college "makerspace" increased their likelihood of visiting the makerspace for extracurricular reasons. These practical experiences of specific technical processes can thus be seen to provide potential mastery experiences that strongly contribute to the development of self-efficacy.

While there are many different styles of active learning, two are of particular interest in this study: experiential learning and project-based learning. Experiential learning, as developed by Kolb [19], centers upon concrete, "hands-on" experience, which is then reflected upon and abstracted, thus enabling application in new contexts. Project-based learning has students engage with course material through projects that encourage the integration and synthesis of previously learned material in order to develop some sort of end product [13]. The benefits of both of these learning styles have been seen in technical fields. In medical/surgical contexts, studies [17],[20] have noted that the practical, hands-on approach of experiential learning can improve both the performance of technical procedures and the confidence of those who are learning them, and that this confidence is positively correlated with the number of times a task is practiced. In engineering, project-based learning is often employed in teaching the design process. As mentioned, both of these methods have been noted for a range of benefits to academic performance and self-efficacy in students, but there seems to be a paucity of data in comparing the effects of these different methods. Thus, tracking student comfort with various concepts after exposure to each of these methods may shed light on how each of them may contribute to students' overall learning and self-efficacy.

1.3. Makerspaces in Engineering Education

"Makerspaces," or areas dedicated to providing resources for product fabrication, are becoming increasingly common in college/university settings [21]. These spaces bring together tools and technologies to facilitate the fabrication and development of products. Typically, these resources are associated with rapid prototyping processes, such as 3D printers, water-jet/laser cutters, and hand/power tools [18]. By collecting these resources in one location, makerspaces increase the ease of access to these resources, but also importantly provide a space for collaborative learning and exchange of ideas [21]. These factors make makerspaces particularly well-suited for providing active learning opportunities in engineering, and indeed, the use and effects of makerspaces in engineering education have been explored in a number of studies [18],[22],[23],[24].

As might be expected from their facilitation of active-learning techniques, the use of makerspaces in engineering education has shown a number of positive outcomes. Hilton et al. [25] found a positive correlation between student-involvement/activity in university makerspaces and in-major GPA. In addition to academic benefits, they also noted that the utilization of makerspaces can improve student self-efficacy. Students that were regularly involved in makerspace activities had higher confidence and lower anxiety about performing engineering tasks than students who did not. This was also seen for students who became involved in the makerspace over the course of a semester. In a study across three different universities, measures of self-efficacy (e.g. confidence, motivation) were seen to be higher in students that voluntarily used the universities' makerspace than in students that did not [24]. When this information is coupled with another study showing that early involvement with makerspaces in a classroom setting led to a greater likelihood of students using the makerspace outside of class [18], it indicates that the incorporation of makerspaces early on in engineering curricula may bring a number of quantitative and qualitative benefits to students' learning experiences.

The nature of makerspaces allows for tailoring which types of active learning are employed within a course. The kinesthetic nature of many of the technologies available in makerspaces provide apt tools for the development of experiential learning opportunities. Their ability to facilitate fabrication and provide a collaborative learning space for students makes them well-suited for their integration into project-based learning in engineering. This is especially true for projects centered around design. This suggests that the utilization of makerspaces may help to reveal potential differences in outcomes from different types of active learning.

2. Methods

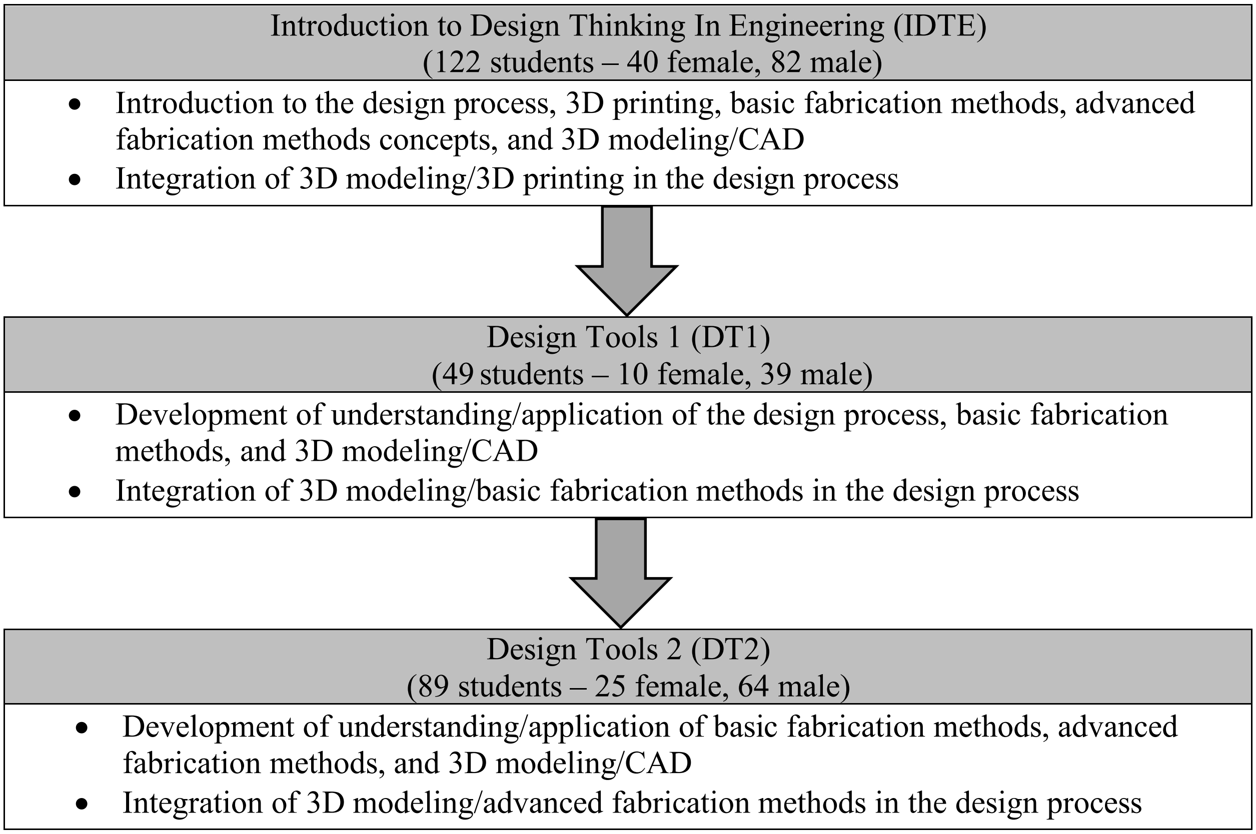
This study used mixed methods to quantify student comfort level with common fabrication techniques in aerospace and mechanical engineering, prior level of exposure to them, and the change in comfort level with them over the course of a semester. Although much of the introduction focused on self-efficacy, this study asked students specifically about their comfort level with particular fabrication methods. Comfort was viewed as an interchangeable metric with confidence, which has been used in previous studies as a proxy variable for self-efficacy [3],[4], and was used in this study due to its likely greater familiarity to the study participants. The study sought to provide insight to what types of classroom activities contribute to increased comfort with these methods. It was approved through the Institutional Review Board for research involving human subjects at the institution where this study took place.

2.1. Participant Selection

The study was carried out with students that were enrolled in 3 required design courses in aerospace and mechanical engineering. The study was conducted at a medium-sized, Midwestern, private university. The courses in the study were all 200-level courses, but can be taken from the second semester of the first year of studies through the first semester of junior year. While the courses are meant to be taken in-sequence, data from this study were collected from each course simultaneously (i.e. the study was not longitudinal and the subjects in the study were not the same for each course). A total of 260 students were enrolled in the 3 courses. 122 students were enrolled in the lowest-level course of the three, 49 in the middle-level course, and 89 in the highest-level course. Instructors for the courses made the study questionnaire available to the students at various timepoints throughout the semester, and study participants were those students who voluntarily filled out the form. No incentives were provided for participating in the study. Responses were anonymous and analyzed in aggregate form.

2.2. Course Sequence

The courses which provided data for this study consisted of three sequential 200-level design courses: Introduction to Design Thinking in Engineering, Design Tools I, and Design Tools 2. The learning goals of these courses were to improve students' understanding and application of the engineering design process, to familiarize them with various fabrication methods commonly used in aerospace and mechanical engineering, and to facilitate the integration of these fabrication methods into the students' own experiences of design, as seen in Figure 1.



Introduction to Design Thinking In Engineering (IDTE)
(122 students – 40 female, 82 male)

- Introduction to the design process, 3D printing, basic fabrication methods, advanced fabrication methods concepts, and 3D modeling/CAD
- Integration of 3D modeling/3D printing in the design process

Design Tools 1 (DT1)
(49 students – 10 female, 39 male)

- Development of understanding/application of the design process, basic fabrication methods, and 3D modeling/CAD
- Integration of 3D modeling/basic fabrication methods in the design process

Design Tools 2 (DT2)
(89 students – 25 female, 64 male)

- Development of understanding/application of basic fabrication methods, advanced fabrication methods, and 3D modeling/CAD
- Integration of 3D modeling/advanced fabrication methods in the design process

Figure 1. Course titles, enrollment, and learning goals for each course analyzed in the study.

Students were exposed to design process concepts through lectures, practical assignments, and multi-week design projects in each course. Students were also exposed to fabrication methods through lectures, practical assignments that had the students directly utilize or perform some of the various fabrication methods, and design projects in each course that incorporated the fabrication methods. All courses in the sequence were designed to intentionally integrate use of the college's makerspace through various assignments and projects throughout the semester.

The first course in the sequence, Introduction to Design Thinking in Engineering (IDTE), sought to provide an introduction to the design process in the context of aerospace and mechanical engineering and some of the common fabrication methods in these fields, from cursory introductions to industrial processes like casting and injection molding, to more involved engagement with basic fabrication and additive manufacturing methods. The course had a short project where students disassembled and reassembled a handheld power tool using basic manual tools. Students also integrated the use of a 3D modeling software and fused deposition modeling-based 3D printing into the design process through a multi-week design project where students designed and prototyped a single tool capable of tightening a number of different mechanical fasteners.

The second course in the sequence, Design Tools 1 (DT1), sought to reinforce the design concepts learned in IDTE while also providing greater engagement with 3D modeling and basic fabrication methods, such as using a band saw, drill press, etc. These basic fabrication methods were integrated into a short individual assignment that required students to do some simple part machining processes on an aluminum bar, including cutting on a band saw, drilling, and tapping a hole. Their use was also incorporated as a requirement in a semester-long design project that had the students design and fabricate a sit-to-stand surface.

The final course in the sequence, Design Tools 2 (DT2), sought to further refine the concepts of the design process and modeling/fabrication from DT1, while also developing familiarity with advanced fabrication methods. Two separate multi-week design projects, one where students used 3D modeling and CNC milling to design and fabricate a fidget spinner, and another where students again used CAD and CAM to design a robot capable of climbing stairs, integrated these methods into the design process.

2.3. Study Design & Research Questions

Students in the courses were asked to complete a questionnaire consisting of eleven questions that asked about their comfort with various fabrication methods in aerospace and mechanical engineering, as well as their prior exposure to these methods, as seen in Table 1. These methods included 3D printing/additive manufacturing (ADD), basic fabrication methods (BAS), advanced fabrication methods (ADV), and 3D modeling techniques (MOD). “Basic” fabrication methods were considered to be those that are primarily manually controlled (e.g. hand tools, power tools, etc.), while “advanced” methods were considered as those that are primarily controlled by computer (e.g. CNC milling, water-jet cutting, etc.). Answers to all questions about fabrication method comfort level and prior exposure were based on a 5-point Likert scale. Students were asked to enter which class they were enrolled in, their gender, and were given the opportunity to provide long-text responses about their prior exposure to these methods. The final timepoint of the study included a twelfth, open-ended question that allowed students to reflect on the effectiveness of the courses in developing their confidence/comfort with the fabrication methods from the survey.

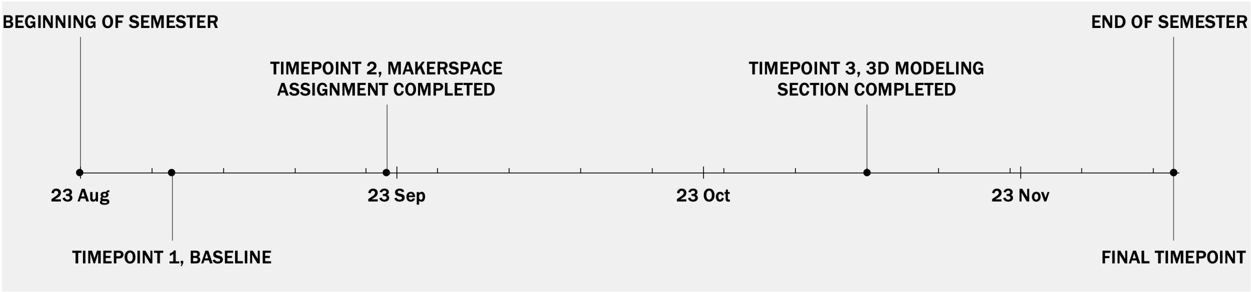
Table 1. Questions Included in Student Survey

1. Which course are you currently enrolled in?
2. To what extent do you agree with the following statement: “I am comfortable with the topic of additive manufacturing (i.e. 3D printing).”
3. What is your level of prior exposure to additive manufacturing?
4. To what extent do you agree with the following statement: “I am comfortable with the topic of basic fabrication methods (e.g. hand tools, drill press, etc.).”
5. What is your level of prior exposure to basic fabrication methods?
6. To what extent do you agree with the following statement: “I am comfortable with the topic of advanced fabrication methods (e.g. CNC mills/routers, water-jet cutters, etc.).”
7. What is your level of prior exposure to advanced fabrication methods?
8. To what extent do you agree with the following statement: “I am comfortable with the topic of 3D modeling (e.g. SolidWorks, AutoCad, etc.).”
9. What is your level of prior exposure to 3D modeling?
10. If you have had any prior exposure to these topics, explain where you encountered them.
11. If you would like to, please type in your gender:
12. How do you feel your class has addressed your comfort/confidence with the fabrication methods included in this survey (especially for the ones used in your class)?*

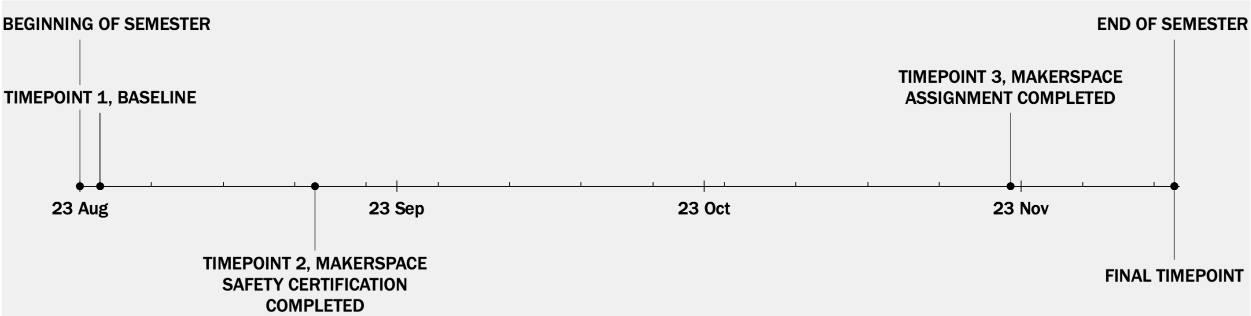
* This question was only included in the survey for the final timepoint.

The same survey was administered to each class at various timepoints throughout the semester, as shown in Figure 2. Due to differences between the courses, appropriate timepoints were determined on a course-by-course basis to correspond with potential exposures to or mastery experiences of different fabrication methods. These included basic introductions to these topics through lectures and more involved exposure/familiarization through practical assignments and design projects which required students to utilize particular fabrication methods from the questionnaire. It was intended that the administration of the survey at the various timepoints throughout the semester would help provide insight into which activities most contributed to student comfort level with the various fabrication methods. It is of note that the final timepoint in each course corresponded with the completion of a multi-week design project.

(a) Introduction to Design Thinking in Engineering Timeline



(b) Design Tools 1 Timeline



(c) Design Tools 2 Timeline

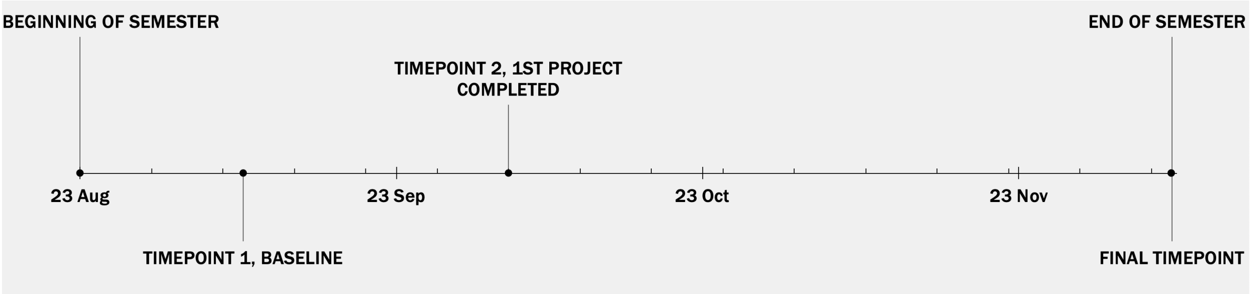


Figure 2. Course-specific data collection timelines were developed for (a) IDTE, (b) DT1, and (c) DT2. The study survey was administered to the participants following the completion of various assignments that incorporated the fabrication methods covered in the survey.

2.4. Data Analysis

Statistical analysis was performed using JMP 17.0.0 (JMP Statistical Discovery LLC, Cary, NC). A *p*-value of 0.05 was considered to be significant for all tests. For tests that analyzed data between/across courses, the third timepoint of DT2 was grouped with the fourth timepoint of IDTE and DT1, as the data for these timepoints were collected at the end of the semester for each course. Data groups with a p-value<0.05 for the Shapiro-Wilk test were analyzed using non-parametric statistical tests. For all figures, bars indicate the mean Likert-scale comfort or prior exposure level associated with each data point. Error bars represent 1 standard deviation. Letters or asterisks indicate different statistical groups ($p<0.05$).

Open responses about prior exposure for the first and final timepoints were semi-quantified by separation into two categories for each fabrication method based on whether all exposure had come from the curriculum from the university in this study, or if the student had outside exposure in addition to this. Blank or ambiguous responses were not included.

3. Results

3.1. Study Participation

Of the 260 students enrolled, 93% participated in the first timepoint. Response rate decreased throughout the study, with 71% participation in the final timepoint at the end of the semester, as shown in Table 2.

Table 2. Overall and Course-Specific Response Rates at Each Timepoint

Timepoint	Overall (%)	IDTE (%)	DT1 (%)	DT2 (%)
1	93	94	77	100
2	63	86	49	40
3	74	84	47	N/A
4	71	83	37	73

Of the participants, not all reported their gender, and analysis of gender effects was limited to those that did. For the first timepoint, 73% of female students and 72% of male students in all courses participated in the study and indicated their gender. This decreased to 42% and 54% by the end of the semester for female and male students, respectively, as detailed in Table 3. Gender effects were not analyzed for DT1 after the first time point due to the small number of respondents.

Table 3. Overall and Course-Specific Response Rates at Each Timepoint by Gender

Timepoint	Overall (%)		IDTE (%)		DT1 (%)		DT2 (%)	
	F	M	F	M	F	M	F	M
1	73	72	85	73	80	59	88	81
2	42	45	65	61	40	41	32	33
3	43	45	60	54	30	28	N/A	N/A
4	42	54	48	47	30	23	60	69

3.2. Aggregate Comfort Level with Fabrication Methods throughout the Semester

Aggregate data on comfort level with each fabrication method for each course were analyzed using a Wilcoxon/Kruskal-Wallis test and a Wilcoxon Each Pair post-hoc test, with timepoint as the grouping factor. Tests showed an increase in student comfort with all fabrication methods throughout the semester in IDTE and DT2 ($p<0.04$). In DT1, significant increases in student comfort level were seen with basic fabrication methods and 3D modeling ($p<0.016$). Mean comfort levels based on course and timepoint with statistical groupings can be seen in Figure 3.

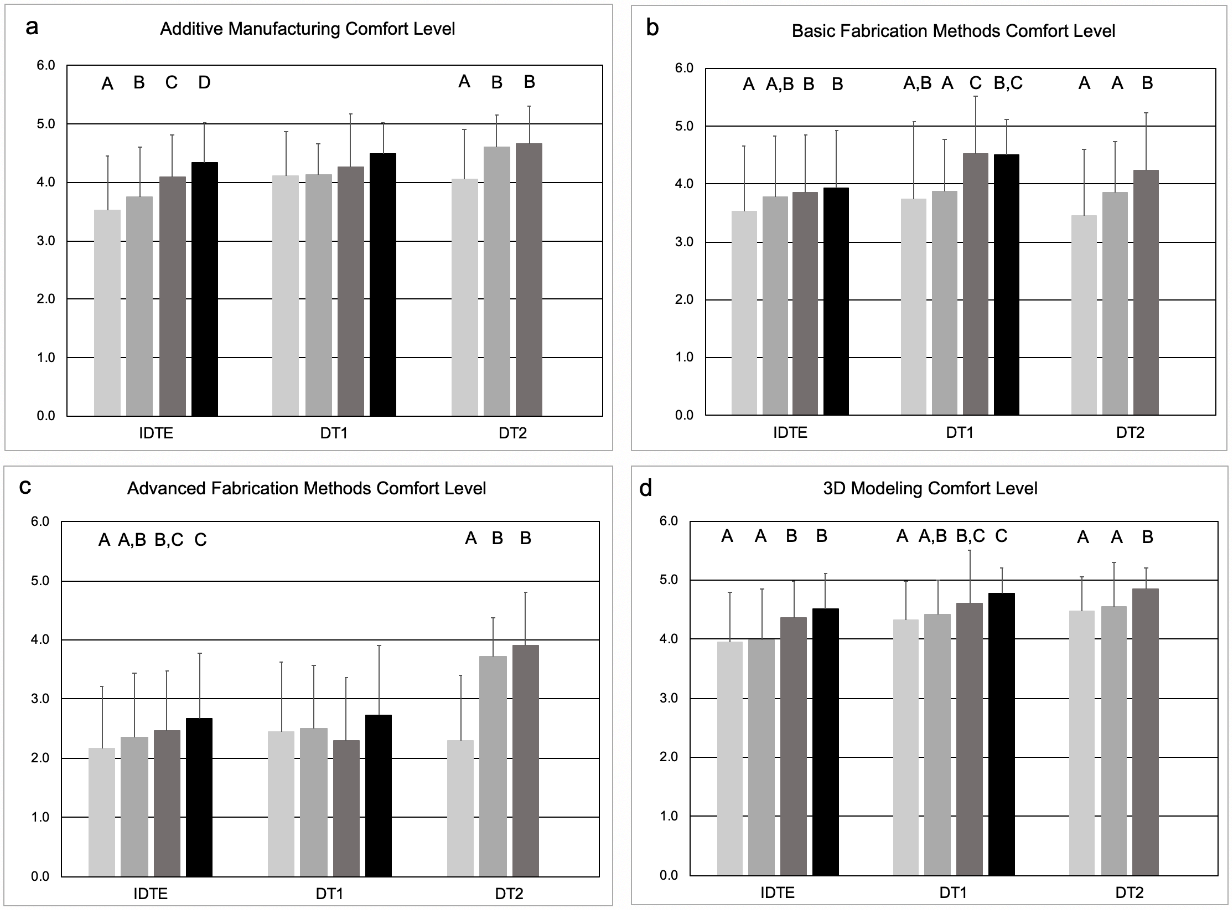


Figure 3. Comfort level with (a) additive manufacturing, (b) basic fabrication methods, (c) advanced fabrication methods, and (d) 3D modeling increased throughout the semester. Letters indicate statistical group.

Standard least squares comparison based on course, timepoint, and their interaction was used to compare the effects of each course on the development of student comfort level with the fabrication methods throughout the semester. Course had a significant effect on comfort level for additive manufacturing ($p<0.0001$) and 3D modeling, with students in DT1 and DT2 having a higher comfort level than IDTE students for both methods based on a least squares means difference student's t post-hoc test. The interaction between time and course had a significant effect on advanced fabrication methods ($p<0.0001$), with the greatest gains seen in DT2.

3.3. Prior Exposure & Effects on Comfort Level

Aggregate data from the first timepoint for all courses on prior exposure level were compared based on fabrication method using Kruskal-Wallis with a Wilcoxon Each Pair post-hoc test. Students reported that they had the greatest prior exposure to 3D modeling, followed by additive manufacturing and basic fabrication methods, and had the least exposure to advanced fabrication methods, as seen in Figure 4.

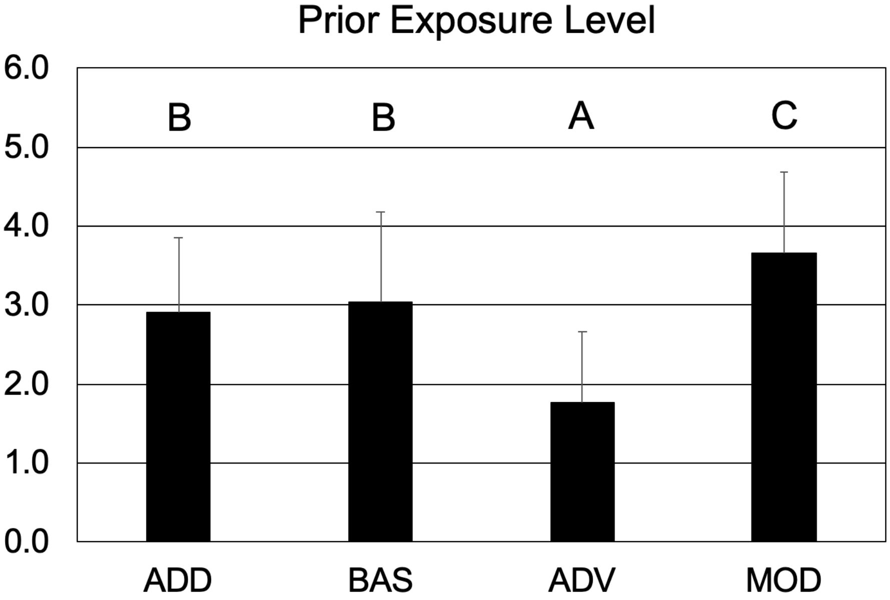


Figure 4. At the beginning of the semester, students across all courses reported that they had higher exposure to 3D modeling techniques (MOD) and lower exposure to advanced fabrication methods (ADV) than to additive manufacturing (ADD) or basic fabrication techniques (BAS).

Using bivariate regression, a significant positive correlation was found between prior exposure and comfort level for each fabrication technique in each course and at each timepoint, with the exception of additive manufacturing in DT1 for the third and fourth timepoints (p>0.05), as well as basic fabrication methods and 3D modeling in DT1 for the fourth timepoint (p>0.05). Standards least squares comparison based on course, timepoint, and their interaction was used to assess differences in exposure level. Course was found to have a significant effect on prior exposure level for 3D modeling (p<0.0001), with students in DT2 reporting significantly higher prior exposure than students in IDTE.

Analysis of open-response data of where students had encountered the different fabrication methods showed some significant effects of outside exposure on comfort level. 176 responses were recorded for the first timepoint (IDTE = 102, DT2 = 74), and 124 responses for the final timepoint (IDTE = 67, DT2 = 57). Data from DT1 were excluded due to lack of respondents. For the first timepoint, least squared means t-tests showed a significantly higher comfort level with additive manufacturing, basic fabrication methods, and advanced fabrication methods for students in IDTE with additional outside exposure to these methods (p<0.05). In addition, students in DT2 with outside exposure to basic fabrication methods had a significantly higher comfort level than those who did not (p<0.05). Outside exposure to advanced fabrication methods trended towards significant effect for DT2 students as well (p=0.058). For the final timepoint, significant effect of outside exposure was only seen for basic fabrication methods in IDTE students (p<0.05), as shown in Figure 5.

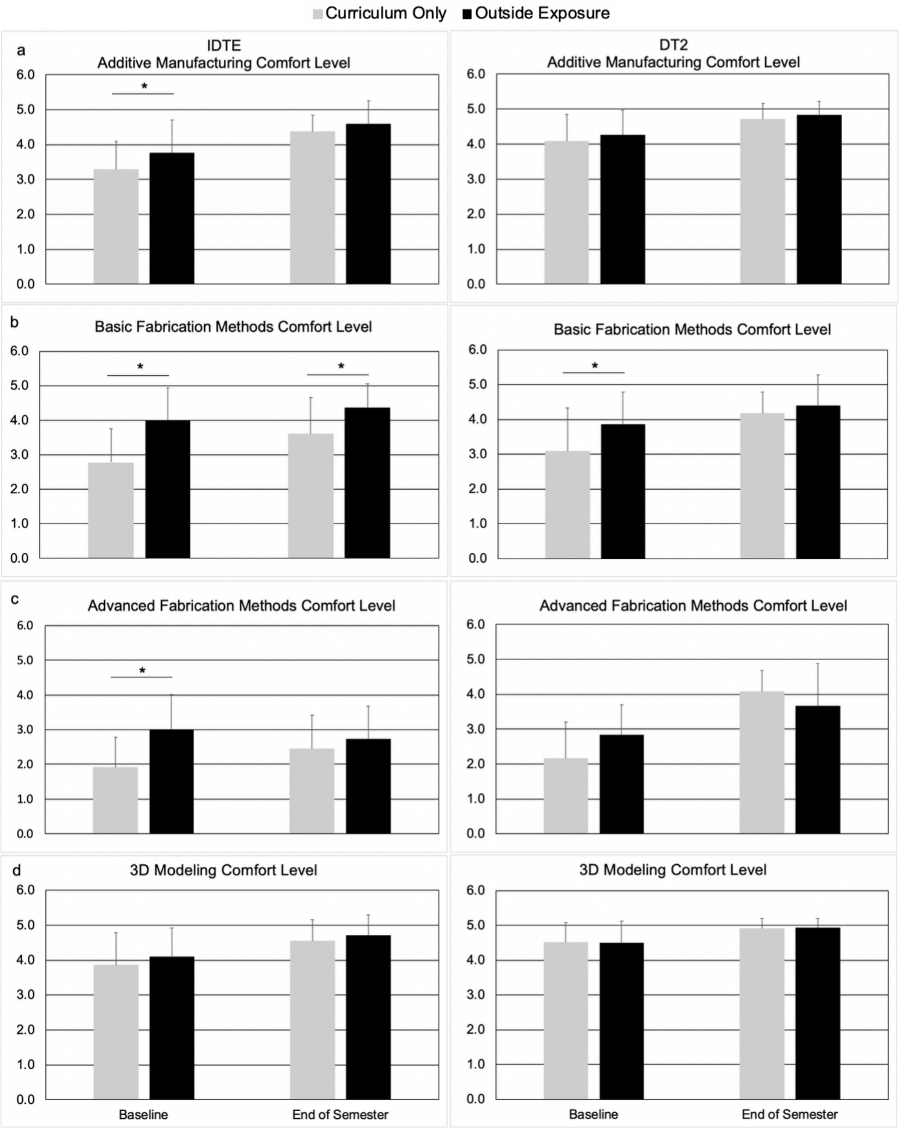


Figure 5. At the beginning of the semester, outside exposure was seen to have some significant effects on comfort levels with (a) additive manufacturing, (b) basic fabrication methods, and (c) advanced fabrication methods for IDTE and DT2 students. These differences were not seen at the end of the semester in most cases. No differences were found between baseline and end of semester data for (d) 3D modeling. Asterisks with bars indicate statistically-significant difference between groups.

3.4. Gender Effects on Comfort Level and Prior Exposure

Kruskal-Wallis analysis of comfort and prior exposure level at the first time point for all three courses showed significant difference only in male and female DT2 students for advanced fabrication methods, with a higher male comfort level ($p<0.05$). In IDTE, differences in comfort and prior exposure level for basic fabrication methods trended towards significance ($p\leq 0.06$), with male students having higher comfort and prior exposure levels. At the end of semester timepoint, these differences were no longer present, although female students in IDTE had a significantly higher comfort level than male students with additive manufacturing ($p<0.0001$).

4. Discussion

4.1. Analysis of Quantitative Results

Throughout the semester, student comfort level significantly increased for every fabrication technique in nearly every course. IDTE saw significant increases in student comfort level with all the fabrication methods from this study. IDTE aimed to introduce its students to all the fabrication methods from this study by traditional lecture, in addition to doing a short practical assignment with hand tools, and a longer, multi-week project involving 3D modeling and additive manufacturing. This suggests that both pedagogical styles: the more traditional, lecture-based approach and the active, practical approach are beneficial to students' self-efficacy. Comfort level with advanced fabrication methods increased in IDTE, where they were discussed in lecture, but not in DT1, where they were neither discussed in lecture nor required for the project. However, in DT2, which required students to use advanced fabrication methods in its projects, students saw a greater increase in comfort level throughout the semester than those in IDTE. These results suggests that, while traditional lecture can be helpful for initial exposure, more active approaches can be more beneficial to developing self-efficacy, especially in areas where students have less prior exposure. This is in good agreement with other studies that have shown that practical assignments can more effectively improve the confidence or perceived self-efficacy of engineering students than exclusively through traditional approaches, like lectures and exams [10],[11].

In DT1, students saw a significant increase in comfort level with basic fabrication techniques at the timepoint that coincided with the completion of a short practical assignment that required each student to use basic fabrication methods to machine a simple part in the college's makerspace. Student comfort level with these fabrication methods did not experience any significant changes in the final timepoint, after the completion of the final project which required further use of basic fabrication methods. This indicates a potential role for experiential learning in engineering curricula, especially in fabrication contexts. The results may suggest that practica are well-suited to the development of competence for specific tasks, like the various fabrication methods used in this study. An analogy can be seen in the medical field, where short practica can be used develop confidence and skill with particular techniques [17]. Thus, for simply learning the processes associated with the fabrication methods themselves, shorter practica may suffice. It is of note that the makerspace-based assignment in IDTE did not lead to a significant increase in comfort with basic fabrication methods, but this may be due to the assignment primarily using common hand tools, to which students may have more prior exposure, rather than machines like drill presses or band saws.

While short practica may be a beneficial practice for developing student comfort with fabrication methods, project-based learning still plays an important role in engineering design. Numerous studies have indicated that integrative projects are well-suited for developing other critical skills in engineering design, like teamwork, communication, creativity, ethics, application of technical knowledge, or the integration of all of these skills in the overall design process, even if they are not necessary for the development of comfort with fabrication techniques per se [26],[27],[28]. Students may thus benefit from the incorporation of both short practical assignments and longer projects that incorporate fabrication methods into the design process in design-based engineering courses.

The only exceptions to the positive trends in comfort level from this study were with additive manufacturing and advanced fabrication in DT1, likely because neither of those fabrication techniques are a point of emphasis in that course. This agrees with the correlation of exposure and comfort level found in this study; students in DT1 had already been exposed to additive manufacturing in two previous courses, and advanced fabrication methods were neither discussed in lectures nor required in its project. These results indicate that comfort/confidence with learning new techniques does not necessarily just develop over time as a student.

Minimal effects were seen from gender in this study. This may be influenced by the mixed/active pedagogy of each of the courses. Stolk et al. [16] noticed decreased gender-based differences in motivation in courses that employed mixed pedagogies. Besterfield-Sacre et al. [29] also noticed few clear gender-based trends relating to confidence in engineering in first year students in a study analyzing three different universities. The results indicate that the incorporation of experiential and project-based learning is equally beneficial for developing self-efficacy for fabrication techniques in male and female student populations.

4.2. Analysis of Open Responses

Open responses for sources of prior exposure to various fabrication methods were most numerous and detailed for the first the timepoint, and revealed that outside exposure had a significant effect on comfort level in IDTE for all fabrication methods except 3D modeling. This is likely due to the fact that students receive instruction and practice in 3D modeling in the college's introductory engineering course that precedes IDTE. At the end of the semester, comfort levels between students who had only been exposed to some fabrication methods through university curriculum no longer had a statistically significant difference from those with outside exposure. This may be due to a number of reasons, including lack of specificity in type and amount of exposure in the semi-quantitative analysis or the decrease in response rate throughout the semester, but it does suggest that practical assignments and projects can be effective for minimizing the disparities in self-efficacy of students who have not had access to fabrication resources outside of university curriculum.

Examination of the final open-response question from the final timepoint asking how the courses addressed comfort/confidence with fabrication methods further supports the conclusions from the analysis of the quantitative data, in addition to providing more qualitative insight. The importance of hands-on experience could be seen in students that either did or didn't feel like there was enough utilization of active learning. One IDTE student claimed:

"I think that the hands on experience with 3D printing helped me become more confident in it. The [lecture-based introduction to hand tools] had given me more knowledge of basic fabrication methods, but I don't feel confident in my ability to use these, as I didn't have hands on experience with them."

A DT2 student also noted that the class had:

"Given me hands on experience to improve my confidence"

In addition, comments suggested that making fabrication resources available is not enough to get students to engage with them, and that there is a benefit to requiring students to engage with these resources, especially makerspaces, as a DT1 student commented:

"This class has forced me to actually see and use the resources in the [makerspace], which I have liked. This class has improved my comfort level and ability in additive manufacturing, 3D modeling, and basic fabrication methods."

While group projects lend themselves well to requiring engagement with fabrication techniques and makerspaces, as mentioned in several comments, practical assignments for individual students may be able to play an important role in ensuring exposure/mastery experiences for all students to help develop their self-efficacy. Group projects may allow some students to avoid working with various fabrication techniques by having other team members do certain tasks, as noted by an IDTE student:

"I feel more comfortable with programs like SolidWorks, but I don't think that I gained much experience with the [makerspace] since our other teammate printed the part and last year the same thing happened. I am yet to print anything myself."

Some students commented on a potentially effective mixed pedagogical style of introducing the technical principles and potential applications of fabrication techniques in lecture, which can then be reinforced through the use of practical assignments and projects:

"We discussed a wide variety of basic tools in class and performed a hand drill decomposition. We also learned more about SOLIDWORKS in lecture and worked on a final project that used relevant skills relating to additive manufacturing. This class has definitely increased my comfort with the fabrication methods referenced in the survey."

"CNC milling well taught through SolidWorks and practice in project one for our own project of the fidget spinner. Great way to be introduced to the topic."

The benefits of such an approach have been seen by Murray et al. in the context of design for additive manufacturing [10]. By introducing students to design principles beforehand, and allowing for opportunities to engage with them in hands-on, concrete design experiences, students can improve both their self-efficacy and technical competence.

Finally, it is important to keep in mind that instructors can play an important role in student self-efficacy as well. One of the DT2 students wrote:

"[Our instructor] has been very willing to help with any issues we might have, so I feel more confident trying things I'm less comfortable with."

4.3. Study Strengths and Limitations

This study has a number of strengths. The incorporation of three sequential design courses, which incorporated similar design principles, but focused on different fabrication techniques allowed for a good level of specificity in characterizing student comfort level with those techniques. In addition, because these courses integrated these techniques into the design process through lectures, practical assignments, and projects, the study was better able to characterize which types of activities contributed to student comfort level.

The study was limited by the anonymous collection of data. Additionally, the data were collected at a single institution over the course of a single semester. These factors may have limited the representativeness of the sample, limiting the study's statistical power, and prevented the ability to track longitudinal effects, either throughout the semester or over longer time periods. The ability to track individual student comfort level would have been particularly helpful in determining the ability of the courses to develop the comfort level of students whose only exposure to fabrication techniques were from university curriculum in comparison to those who had additional outside exposure to these techniques. The current study only distinguished between students who had no exposure to fabrication techniques outside of the university curriculum and those who had any level of outside exposure. Tracking individual student responses would have allowed for greater specificity in tracking comfort level throughout the semester based on the students' initial characterization of their prior exposure level. As it stands, the semi-quantitative results were applied using broad categorization, and thus caution should be used when interpreting the results. In addition, lower response rates at the end of the semester, especially for open response questions about prior exposure sources and gender, also suggest the use of caution in discerning trends from the results.

5. Conclusion

5.1. Major Trends

The results of this study demonstrate the effectiveness of hands-on learning in developing student self-efficacy. Student comfort increased with every fabrication method that was used in the courses of this study, and open responses showed that active learning played an important role in this. This is particularly important for areas where students have little prior exposure, such as with advanced fabrication techniques like CNC milling or the use of water-jet cutters. This study supports that project-based learning is well-suited to developing students' self-efficacy with the use of fabrication techniques, but also indicates that shorter practical assignments, typical of experiential learning styles, can still be effective in developing student comfort/confidence in the performance of the techniques themselves. In addition, student responses in this study also support the integration of makerspaces into courses where possible. Makerspaces can provide a number of resources for hands-on experiences that students may not utilize if not required to do so. When these teaching strategies and resources are used with more traditional introductions to the principles and concepts underlying the fabrication techniques, it may provide a strong pedagogical means of developing self-efficacy for students to use these techniques in future contexts.

5.2. Future Directions

This study provides further data and support for the effectiveness of active learning, while helping to distinguish between the effects of experiential learning and project-based learning in engineering design. Future longitudinal studies that could track the development of student comfort throughout the entirety of the 3-course sequence would provide greater insight to how student self-efficacy with fabrication techniques develops over time. Further, studies that could provide closer analysis and greater distinction between sources and levels of outside exposure could help in determining which types of activities most contribute to student self-efficacy in fabrication. In addition, further characterization of the differences between the effects of shorter experiential learning activities and longer, integrative projects on student self-efficacy could provide further insight to engineering curriculum development. Analyzing the effects of requiring students to use makerspaces through these learning strategies, especially in early courses, on their usage of makerspaces in other contexts, such as in capstone design courses, could yield further insight to the dynamics and potential benefits of integrating makerspaces earlier and more regularly into engineering curricula. Finally, it would be interesting to see if there are any ways to utilize increased comfort with one technique to improve confidence with other techniques, and thus develop "self-efficacy for learning" [4],[30] in the context of learning new technical engineering skills.

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