3D printing to introduce design in a cornerstone project

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ABSTRACT: First-year engineering students from a public university took part in a semester long design project. The honours students (1 section or approximately 20% of the class) had an additional project that involved designing a team logo and using 3D printing technologies to create an initial prototype and, then, to revise their design before creating a final logo design. The current study sought to assess using 3D printing technologies as an educational method for learning about the design process. Honours students participated in three anonymous surveys. The surveys were administered at: 1) the start of the semester; 2) after the first prototype was printed; and 3) after the final prototype was printed (end of the semester). The non-honour students were also surveyed related to their engineering project experience (which all students completed). Honours students reported progressively higher interest levels and project relevance at each survey throughout the semester. Further, honours students reported a higher level of learning and experience with the design process at the end of the semester than non-honours students. Finally, there were no statistically significant differences for women. Using 3D printing technologies is a meaningful and effective approach for introducing engineering students to the design process as they found it to both be interesting and enjoyable.

Keywords: First-year engineering, 3D printing, cornerstone design

INTRODUCTION

A key aspect of maintaining global competitiveness for the United States is to graduate a sufficient number of qualified engineers to support a growing industrial base [1][2]. To meet this demand, engineering educators seek to remove road blocks that deter students from persisting in engineering, while maintaining the academic integrity of the discipline; in short, to attract and retain qualified students [3]. One way engineering educators can remove road blocks is by changing traditional ways of educating engineers [2]. There is a wide range of research citing the need to transform traditional lecture courses into more interactive and responsive environments [4-7].

In general terms, the distinguishing attribute of engineering is design; design has been incorporated throughout engineering curricula beginning in the first-year with cornerstone design and concluding in the final year of engineering study with capstone design, which are often referred to as project-based learning (PBL) experiences. In particular, cornerstone design projects are thought to increase student interest in engineering, increase retention, motivate future engineering courses and enhance performance in future PBL experiences [8].

Project-based learning experiences have been recognised as the best educational practice [9-10] for heightened student engagement [11][12]. Cooperative, project-based learning experiences grounded in a broader societal context have been recognised as positive influences for all students, including underrepresented groups, such as women and minorities [13-15]. Engineering differs from other academic majors by: 1) the low numbers of women enrolled; and 2) the matriculation of students out of the programme (very few students migrate into engineering from other majors) [16].

In particular, women enter with similar levels of academic preparation to their male peers, but leave engineering earlier in their academic pathway despite being in good academic standing [6][17]. Given that cornerstone projects are an opportunity to increase student interest and retention, it is critical that projects used as educational experiences are of interest to both male and female students.

In order for a cornerstone project to conform to educational best practices the focused learning objective is on *design thinking*, which relates to: handling uncertainty, making decisions as part of a team, technical communication and viewing design as an iterative process [8]. Offering engineering students access to rapid prototyping is a novel approach to understanding the iterative nature of the design process [18]. Design experiences can be facilitated by the use of 3D printing technologies [18-20]; in fact, the use of 3D printers within the educational setting has increased significantly over the past several years. With fused deposition modelling (FDM) printers becoming more affordable [21], the expansive growth and accessibility of such 3D printers is an opportunity to revolutionise STEM (science, technology, engineering and mathematics) education by allowing for technology driven iterative design experiences [21].

A study by Jaksic and associates found that students designing and *printing* their own objects provides the greatest amount of interaction possible [18]. Another study by Johnson and associates found that the use of 3D printers was an effective tool for a graphics design course in which students were asked to recreate a 3D printed object given 3D CAD software. Throughout the duration of the course, the students were given multiple, iterative design opportunities to further advance their original designs and by the conclusion of the course all students successfully recreated the original design [19].

One of the wide-spread impacts of low-cost, entry level 3D printers is on STEM education. Several studies have highlighted the positive role of 3D printing along with traditional tools (subtractive manufacturing and design optimisation), particularly in the case of undergraduate STEM education for design-prototype and manufacture projects [22-24].

Overall, the development and implementation of courses that utilise low-cost, entry level 3D printers for K-12, undergraduate, graduate and distance education students has the potential for significant impact [25]. With only a few prior educational studies on the use of low-cost, entry level 3D printers in design project experiences, the current study sought to assess student perceptions in a first-year engineering cornerstone design course, which address the following research questions.

Research Questions

1. Does the use of 3D printing in a first-year engineering design project increase student interest in the engineering project?
2. Does the use of 3D printing in a first-year engineering design project increase students' view of the project's relevance?
3. Does 3D printing in a first-year engineering design project increase student learning and understanding of design as a process?
4. How enjoyable do women and men find engineering design experiences that utilises 3D printing?

Background of the Institution Studied

The institution studied was an urban, public, Master's comprehensive university located in the Midwest with a wide variety of higher education programmes and majors serving ~13,000 undergraduate students, 86% of which come from within the state. It is a very accessible school for students of diverse academic preparations and socioeconomic backgrounds. The demographic makeup of students with a science or engineering background is 72% male and 28% female and ~12-15% minority student population (5% Hispanic, 3% African American, 2% international, 1% multi-racial and 1% Asian). Most of these students are of traditional college age (80% less than 25 years old), are full time students (85%), and live off campus and commute (90%). Within the sciences and engineering, there was a total undergraduate fall enrolment of 2,729 students.

Background of the Course Studied

The engineering programme at the institution studied has a First-Year Engineering Programme, which means that students take the same courses regardless of which engineering discipline they plan to pursue for further study. At the end of the first-year, students are asked to *declare*, which discipline they wish to pursue and are subsequently advised to enrol in courses for the following semester (starting in the sophomore year).

The First-Year Engineering Programme is a two semester course sequence, with a two credit course in the fall (Engineering Concepts) and a two credit course in the spring semester (Engineering Computing). There are two design projects in the Engineering Concepts (fall) course and one design project in the Engineering Computing course (spring). All students complete these courses/design projects but, there is a separate honours section of the course that includes experiences with 3D printing/additive manufacturing. The honours students also: go on a tour of AmericaMakes (the National Additive Manufacturing Innovation Institute), listened to a class presentation on 3D printing, had their design from the fall semester course 3D printed and participated in an iterative design of a team logo for the spring semester course.

METHODS

A formal study of the first-year engineering cornerstone courses was conducted during the 2014-2015 school year. In particular, the honours students were surveyed at three points throughout the school year and were compared to the other sections of the course, which did complete a design project, but did not have any of the enrichment experiences related to 3D printing. The 3 surveys were conducted at the following times: 1) after the conclusion of the first course; 2) after the first-design iteration in the second course; and 3) at the conclusion of the first-year engineering course sequence as shown in Figure 1.

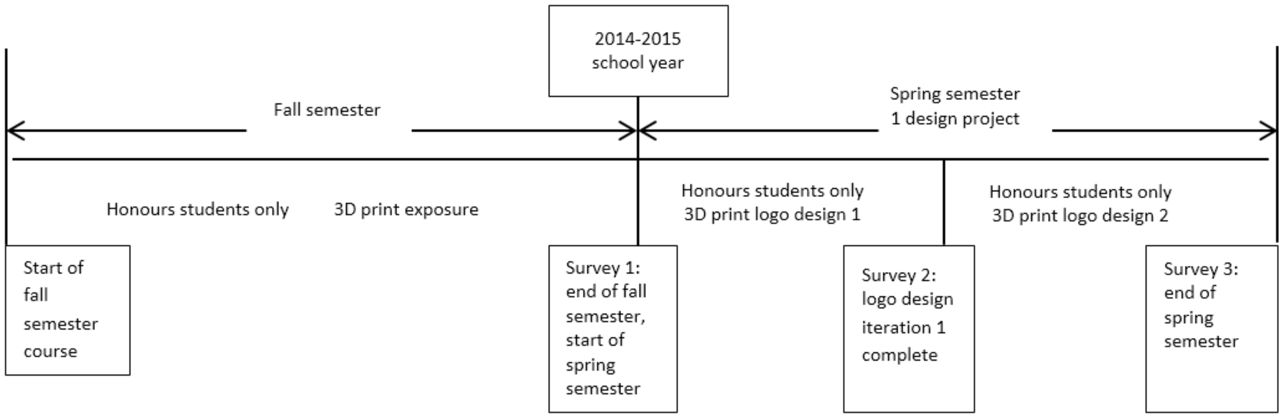

Figure 1: Timeline of survey administrations.

Each of the surveys were administered on-line using BlackBoard, since it is the tool used for all course assignments. Responses were anonymous; however, students were given course credit for each survey completed. Collectively, there were 110 responses from honours students, of which 77 were male, 31 female and 2 unknown with an average response rate of 93%. For Survey 3, both honours and non-honours students participated.

Table 1: Summary of student respondents.

Surveys	Honours students			Non-honours students		
	Actual respondents	Potential respondents	Response rate	Actual respondents	Potential respondents	Response rate
Survey 1	38	44	86%	N/A	N/A	N/A
Survey 2	35	37	95%	N/A	N/A	N/A
Survey 3	37	37	100%	127	133	95%
	110	118	93%			

Summary statistics are reported, as well as Wilcoxon rank-sum tests of statistical significance were evaluated. Rank-sum tests are a non-parametric test that does not assume a normal population distribution [26]. All of the questions were on a Likert scale, and the quantitative responses were coded, such that a more positive response was a higher value and a less positive response was a lower value. Statistical analysis was conducted using the statistical software package STATA®.

Three different material extrusion printers were used for 3D printing of the student models in this study. A Makerbot 2X, an UP! Mini and a third generation cube demonstrated the process of 3D printing to the students. Since the student models had sizing constraints of under 3” cubed, print dimensions did not affect, which printer was to build each individual model. The Makerbot and the UP! Mini printers used 1.75 mm diameter acrylonitrile butadiene styrene (ABS) filament, while the cube used 1.75 mm diameter polylactic acid (PLA). Using both polymers did not affect the overall outcome for the students. Since the models created by the students are solely aesthetic rather than structural, it was a good learning experience for the students to witness the visual and rigidity difference between each polymer. All printers were set to the best quality settings, using similar nozzle speeds and flow rates.

The students went through three total experiences with a 3D printer: 1) a car modelled after edible goods; 2) team logo (first iteration); and 3) team logo (second iteration). The purpose of the edible car project was to offer students an opportunity to collaborate with peers in a first design exposure in which all students had the same challenge, but there were many designs that could achieve the design objectives. The first 3D printing experience to create the car model was limited. Students submitted a Solidworks Part (.sldprt) file and the teaching assistant determined orientation and printing speeds. The students did not a have first-hand involvement with a 3D printer during this experience.

The second 3D printing experience for the honours students was to create a team logo, which was an ornamental design (non-functional); however, the 3D printing was more involved/interactive than the edible car. This included the conversion of their SolidWorks® model to a .stl file for printing, the setup and slicing of their model using the printer’s software and physical encounters with the printer. On the scheduled day of printing, each group was individually brought into the 3D printing laboratory to learn and evaluate their model before actually printing.

The students were briefly introduced to the way .stl files work, the different types of 3D printing and polymers, and the types of printers the University has available. Upon ending, each group witnessed its own model being processed through the slicing software corresponding to the printer in use. The group ultimately determine of which orientation is most practical to use the least amount of material, reduce post processing time and exhibit the best overall product for their team logo. The entire class evaluated each of the designs and voted for: best/favourite logo design (they could not vote for their own) and which design used the least amount of material.

An iteration on the team logo design was the final 3D printing experience. The students had the opportunity to update/revise their logo design after seeing the 3D printed part of their own design, as well as their classmates. This process was nearly identical to the second, but required the students to interact with the 3D printing process even more. This time, the students were asked to convert their logo to a .stl file individually and decide, which type of material was most practical for their model. Each group individually witnessed the beginning and end of their model being printed. The class again voted for the best/favourite design after the second design iteration.

RESULTS

The honours students that participated in this project were asked about their prior experience with both solid modelling, as well as 3D printing. Table 2, shows that prior to taking the first-year engineering courses the majority of students were aware of solid modelling as a tool, but did not have any experience with using it. In terms of 3D printing, most students had no prior experience (but were aware of it) or limited observational experience. There were a few students in the course that had experience with solid modelling or 3D printing.

Table 2: Summary of prior student experience.

Survey questions on experience prior to taking the course	No prior knowledge	Knowledge of existence, but no experience	Limited observational experience	Some prior experience/ exposure	Substantial prior experience/ exposure
Had you ever been exposed to any form of solid modeling software (Solidworks, AutoCAD, ProE, etc)?	15.79%	52.63%	7.89%	10.53%	13.16%
Had you ever been exposed to 3D printing?	5.26%	42.11%	44.74%	2.63%	5.26%

As part of the first 3D printing design experience, student project teams created a SolidWorks model of their design and it was printed by the TA (students did not have any observational or hands-on involvement with the printing process). An example of a 3D printed part from a student project is shown in Figure 2.

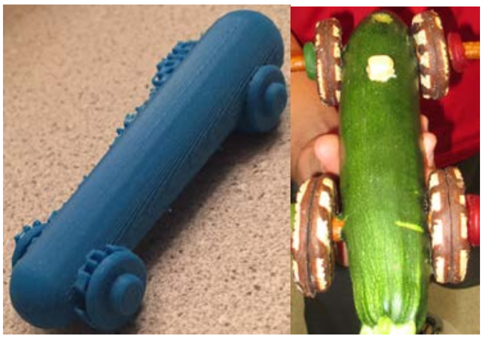

Figure 2: Example of a 3D printed model car (left), edible car physical model (right).

For the team logo design (first iteration), student project teams: 1) created a SolidWorks model of their design; 2) converted the file to a printable .stl file; 3) met with the TA to set up the 3D printer (including determining the model orientation for printing and slicing); 4) observed the 3D printed part after 1 hour progression; and 5) received the final printed model. Figure 3 shows the model that was voted the favourite/best design as selected by the entire class (for both iterations).

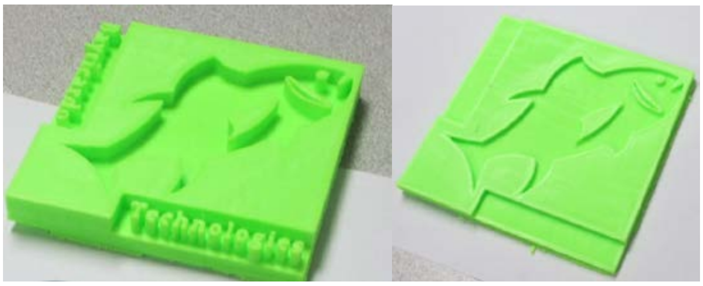

Figure 3: Favourite design (left - iteration 1/right - iteration 2).

For the second iteration of the team logo design, student project teams: 1) created a SolidWorks model of their design; 2) converted the file to a printable .stl file; 3) met with the teaching assistant to set up the 3D printer including determining the model orientation for printing and slicing, select printing speed and print material; 4) observed the 3D printed part after one hour of printing; and 5) received the final printed model. Figure 4 shows a design iteration where the team greatly reduced the printing time and material usage.

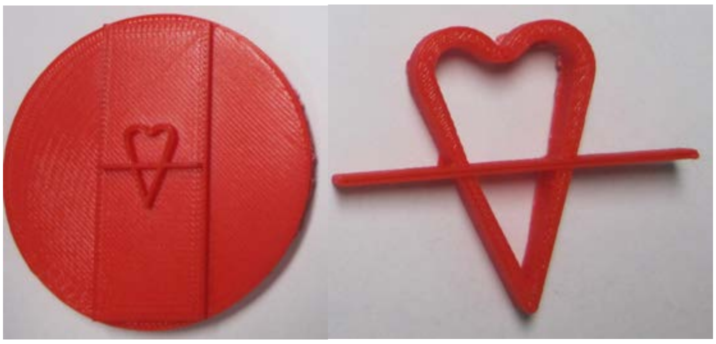

Figure 4: Logo example with material reduction (left - iteration 1/right - iteration 2).

The honours students responded to surveys after each of the three 3D printing experiences and the results are shown in Table 3. By comparing the means using a Wilcoxon rank-sum test for statistical significance, the difference in responses from Survey 1 to Survey 3 were not statistically significant.

Table 3: Comparison of student responses across three surveys.

Survey questions on a Likert scale out of 5 (higher value is a more positive response) related to 3D print design project	Mean value (all students)		
	Survey 1	Survey 2	Survey 3
Interesting learning experience	4.32	4.18	4.33
Relevant learning experience	4.03	3.97	4.24
Valuable engineering design experience	4.03	4.11	4.00
Increased interest in 3D printing technologies	3.94	3.94	4.08

Student responses to the same questions were also evaluated by gender and are reported in Table 4. In comparing male and female student responses (for all three surveys combined), there were no statistically significant differences, indicating male and female students had similar interest levels, and perceptions of the relevance and value of the experience. Looking at the overall perceptions reported on the final survey (Survey 3) at the conclusion of the course sequence, the same metrics were evaluated for male and female students and again the ratings were positive and there were no statistically significant differences between male and female students.

Table 4: Comparison of student responses by gender.

Survey questions on a Likert scale out of 5 (higher value is a more positive response) related to 3D print design project	Mean value for all surveys combined	
	Male students	Female students
Interesting learning experience	4.28	4.27
Relevant learning experience	4.13	3.97
Valuable engineering design experience	4.08	4.00
Increased interest in 3D print technologies	3.90	3.97

For the logo design iteration (the last two surveys), students were asked about their involvement in the 3D printing project, such as creating the SolidWorks model, proposing concepts for the model, discussed revisions or was not involved. Only two students indicated they were not involved in creating their logo design, but given that creating the actual model in SolidWorks on the computer could be viewed as an individual task, it was thought it would be a differentiating factor in student experience (how interesting/relevant they found the project); however, it was not.

In comparing the student responses based on their perceived role in the logo project yielded no statistically significant differences in their reaction to the project.

In working on the logo design, which had two iterations, students were asked after receiving the 3D printed part of each iteration how satisfied they were with the result. Table 5 shows the mean results and the rank sum comparison; the satisfaction level increased after the second iteration and the difference was statistically significant.

Table 5: Comparison of satisfaction with the 3D printed logo.

Survey questions on a Likert scale out of 5 (higher value is a more positive response)	Mean		Rank-sum *p* value
	Survey 2 (Logo iteration 1)	Survey 3 (Logo iteration 2)	
Satisfaction with 3D printed part	3.82	4.19	0.003**

Note: ** denotes $p < 0.01$

All students participated in design projects as part of the First-Year Engineering Programme; however, only honours students participated in the 3D printing experiences. Using the non-honours students as the baseline group for comparison, students were asked two questions on the final survey that related to learning the engineering design project as part of the course and the results are summarised in Table 6. The differences in student perception for learning the design process are statistically significant wherein honours students reported higher perceived learning gains.

Table 6: Baseline comparison of value in using 3D printing to teach design process.

Survey questions on a Likert scale out of 5 (higher value is a more positive response)	Mean		Rank-sum *p* value
	Honours	Non-honours	
Indicate to what extent you agree: by taking this course I gained significant experience in the design process	4.54	4.17	0.034*
Indicate the extent to which this course met learning objectives to engage in an open ended design process	4.71	4.32	0.036*

* denotes $p < 0.05$

Returning to the Research Questions

Each of the research questions is revisited and related student quotes from the free response items of the survey are introduced.

1. Does the use of 3D printing in a first-year engineering design project increase student interest in the engineering project?

   Yes, with each 3D printing experience students reported an increased interest level.

   The 3D printing that was showcased really peaked my interest in what we can do in the future with 3D printing, as well as how beneficial it will become to our society in the future.

   I had seen some 3D printing before ENGR 1550H but it was cool to have my own design printed. If there was a course available relating to 3D printing/rapid manufacturing, I would most likely take it.

2. Does the use of 3D printing in a first-year engineering design project increase students' view of the project's relevance?

   Yes, with each 3D printing experience students reported higher recognition of project relevance.

   3D printing is really interesting in all aspects, and it is a relatively new technology that is going to be utilised more and more, so I think it only makes sense to incorporate it into the curriculum more.
   I thought modelling the edible car in SolidWorks and 3D printing was very relevant and applicable to this course and engineering in general.

3. Does 3D printing in a first-year engineering design project increase student learning and understanding of design as a process?

   Yes, the students that had 3D printing experiences (honours students) reported higher agreement that the learning objective for learning the design process was met than the students that did not participate in the 3D printing experiences (non-honours students) (statistically significant).

   3D printing was an interesting experience. Having learned some about the functionality and utility of 3D printers, I feel intrigued to learn more.

I enjoyed the added logo assignment. I believe it promoted the design process and allowed for creativity among students.

4. Do male and female students perceive engineering design experiences that utilises 3D printing similarly?

   Yes, there were no statistically significant differences between male and female students in their interest, perceived relevance, or value as a design experience.

   The 3d printed logo was really fun! (female student).

   It is awesome. I think that we should do more 3D printing! (male student).

CONCLUSIONS

Design is a key element of engineering; and engineering education research has recognised the value of using design project-based learning experiences to teach students starting in the first year of engineering about this process through cornerstone design. The nature of design is a continuous process wherein engineers continue to re-evaluate the needs and make improvements, and the rapid growth and accessibility of 3D printing technologies makes it an effective and affordable tool to allow students to physically see the changes they make to a design.

Teaching design in an academic setting, which must adhere to the time constraints of the institution, such as semesters or quarters is somewhat artificial, so using 3D printing as a rapid prototype method allows students to design and redesign multiple times, because of the short lead time. Further, any opportunity to take a design from a computer design concept to a physical item is meaningful for visualisation. The reaction from both male and female students was equally positive, and they recognise using 3D printing technologies as an interesting and relevant approach to learning the design process.

The current study was limited to a single course administration and is based on self-reported data from the students enrolled in the course. The study would benefit from additional administrations at dissimilar institutions.

In terms of the project itself, it could be improved by allowing the students to 3D print functional parts - as opposed to the team logos, which were aesthetic rather than functional. Using 3D printing technologies for functional parts would expose them to other facets of design, such as design clearances, geometric dimensioning and tolerancing, and how changes to their design influences design performance.

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BIOGRAPHIES

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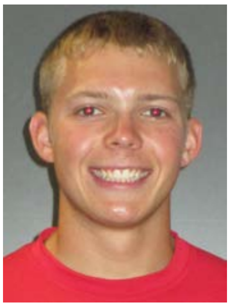

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