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The Cumulative Effects of an NSF-Funded Additive Manufacturing Course at Three Large State Universities and Their Surrounding Communities

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Abstract: This paper is the culmination of four years of an NSF-funded project implementing and assessing an undergraduate additive manufacturing course at three large state universities: Texas Tech University, Kansas State University, and California State University – Northridge. The research questions addressed are:

(1) What are the changes in skill and knowledge concerning additive manufacturing experienced by undergraduate students?

(2) What is the effect of this course on attitudes towards engineering and self-efficacy in engineering for enrolled undergraduate students?

The sample consists of four years of data from the undergraduate students enrolled in the course at all three universities (combined N = 196). Our method for data collection was matched-pair surveys that contained both (i) an assessment for content knowledge and (ii) an attitudinal assessment previously validated in published research for data collection about attitudes towards engineering. Matched-pair surveys means that we collected data from Student X at Time 1 (before being taught) and then again from at Time 2 (after being taught) and are able to directly compare any change in content knowledge or attitude within the same person. We also collected demographic information to be able to see whether changes in, for example, women differed from those in men.

All undergraduates experienced statistically significant increases in content knowledge and additive manufacturing skills. In an intriguing finding, female students outperformed male students, which fits with the research that indicates that engineering courses which emphasize pragmatic and real-world applications, as well as those that use group work, will disproportionately help underserved engineering populations like women and people of color succeed. Fitting with the above finding, undergraduates noted that they perceived that they had increased in teamwork, communication, and computer programming skills. These gains were particularly high in female students and students of color.

Introduction:

Additive manufacturing (AM) is a type of manufacturing process during which materials such as polymers, metals, and ceramics are deposited in a layer-by-layer stratigraphy to create a three-dimensional part based on the schematics of a computer-aided design (CAD) [1-5]. Additive manufacturing is now a widely used process in industry [6], higher education, medicine [7], and K-12 classrooms [8].

As a manufacturing process, AM upends traditional manufacturing, in which parts are generally made in a centralized factory with specialized equipment and then shipped to customers. Traditional manufacturing, as the current supply chain issues have overtly demonstrated, can be slowed or stopped altogether based on any issues in materials requisition, factory issues such as missing parts for broken machines or labor shortages, and transportation problems. Because AM is not based on centralized manufacturing the same way as traditional manufacturing, it can avoid some of the problems that plague traditional manufacturing and also be less environmentally harmful because it avoids much of the pollution associated with transportation of products.

The current global value of AM products and services has grown considerably in the last decade. While is it difficult to put a precise number on a manufacturing process that is, by its very nature, decentralized, some experts note that its value has expanded from just under $2 billion in 2017 to nearly $14 billion in 2022, with an expected annual growth rate of about 21% [9].

Given the above, it was surprising that, as of this grant's beginning in 2017, there was a dearth of undergraduate engineering courses focused solely on additive manufacturing. That year, we surveyed about 100 other research-based universities with schools of engineering and found none with an undergraduate class specifically on additive manufacturing. Thus, we created one and applied for a grant from NSF in order to determine the class' effects on students. The primary investigators for this grant are three engineering professors at large state schools (respectively, Texas Tech University, Kansas State University, and California State University-Northridge) and one sociology professor (Texas Tech University) who specializes in course and individual educational assessment. Both Texas Tech and Kansas State are R1 universities and grant doctorates in engineering. Texas Tech is a Hispanic-Serving Institution (HSI). California State-Northridge predominantly serves undergraduates and has a disproportionately large population of immigrant and first-generation college students.

Our research goal was to determine the effects of this grant on undergraduates' knowledge and skills. We additionally wanted to determine whether this class affected their attitudes towards engineering as well as their self-assessment on different skills needed to be engineers. This attitudinal assessment is one that was previously inductively developed on engineering undergraduates and validated in multiple previous studies [10 and 11]. Both the knowledge assessment and the attitude assessment can be seen in Appendix A. Our previously published papers with data by year can be see in papers [12-14] in the bibliography.

As part of the class, we also invited local middle- and secondary students into our laboratories for field trips to learn about AM and its place in STEM. We found this to be particularly effective in teaching our undergraduates communication and teamwork skills, in that they needed to teach the younger students in groups. While we have three years of data from the younger students (N=212) that will be analyzed in a separate paper, the focus on this paper is five years of data from our undergraduates (N=196).

Thus, our research questions are:

(1) What are the changes in skill and knowledge concerning additive manufacturing experienced by undergraduate students?

(2) What is the effect of this course on attitudes towards engineering and self-efficacy in engineering for enrolled undergraduate students?

Methods:

Sample: The data consist of five years of matched pair surveys from the undergraduate students enrolled in the course at all three universities (combined N = 214). Texas Tech University is a Carnegie R1 university that enrolls more than 40,000 students through both in-person and online programs. It is a federally designated Hispanic Serving Institution. Kansas State University is also a Carnegie R1 university and enrolls about 25,000 students. It is a land-grant university. California State University-Northridge is a predominantly undergraduate-serving institution and enrolls about 35,000 through both in-person and online programs.

Given the large sample size, we have been able to decompose the groups based on salient characteristics like gender, first-generation college student status, race, and major. Occasionally, there was a student who added the course late or who dropped the course before completion. These students (11 students) were dropped from the analysis. Only students with data from both Time 1 and Time 2 were included in the analysis.

Data Collection: Our method for data collection was matched-pair surveys that contained both (i) an assessment for content knowledge and (ii) an attitudinal assessment previously validated in published research for data collection about attitudes towards engineering. Matched-pair surveys means that we collected data from Student X at Time 1 (before being taught) and then again from at Time 2 (after being taught) and can directly compare any change in content knowledge or attitude within the same person. We also collected demographic information to be able to see whether changes in content knowledge or attitudes differed by gender, race, major, and first-generation college student status. We changed race into a binary variable (white vs. non-white) to be able to have the results be statistically meaningful. There were not enough people of, for example, Black or Native American self-identification for the category to be meaningful. In cases where the numbers do not total 214, this is due to a lack of data about the student's demographics.

Data Analysis: Once collected, we discarded the data from students who only took the survey at Time 1 or Time 2. This occasionally occurred because a student might add the class after the initial data collection or drop the class before the second data collection. We conducted paired-samples T-tests, which allowed us also to measure any change in sub-groups such as by gender, major, race, and first-generation college student status.

Results:

Content Knowledge:

The compiled data from years 2018-2021 can be seen in Appendix B. We will present results from 2022 at the conference, but the full data from 2022 won't be available until after the end of the semester, due to the data collection structure.

In looking at the pooled data over four years of teaching this course at three different universities, we can see that students at all three universities experienced statistically significant increases in knowledge and skills at all three universities for all the years surveyed. Previous years' data can be found in our previous papers, listed as [12-14] in the bibliography. The students at Texas Tech increased by 17.1 points, the students at Kansas State increased by 15.9 points, and the students at CSUN increased by 14.88 points. This is on a 0-45 point scale. All results were significant ($p<.001$).

Due to the large sample size, we were able to decompose groups by gender, race, and first-generation college student status. We additionally collected data on year in college (freshmen through senior) but there were so few underclassmen that these categories were not statistically meaningful. We also collected data on major, but the students were predominantly mechanical engineering or industrial engineering majors, so these categories were also not statistically meaningful.

In an intriguing finding, female students outperformed male students by more than two points. Women on average increased by 14.9 points ($p<.01$), while men increased by 12.7 points ($p<.01$). These differences were also statistically significant ($p<.05$). White students increased by 15.1 points ($p<.01$), while non-white students increased by 16.9 points ($p<.01$). These differences were also statistically significant ($p<.05$). First generation college students and non-first-generation college students also experienced increases of 13.6 and 13.87 points ($p<.01$), respectively, although there was no statistically significant difference between their increases. From this, we can say that women and students of color experienced higher increases in content knowledge than men and non-students of color, respectively. There was no difference in growth due to first-generation college student status when all the years were collated. This fits with the previously-cited research that indicates that engineering courses which emphasize pragmatic and real-world applications, as well as those that use group work, will disproportionately help underserved engineering populations like women and people of color succeed.

Attitudes and Self-Efficacy

Fitting with the above finding, undergraduates noted that they perceived that they had increased in teamwork, communication, and computer programming skills. As noted above, self-efficacy is a subjective metric, but particularly important in determining tenure in engineering as well as desire to stay in an engineering major. On a 1-5 scale, students noted increases in teamwork skills (+.6), communication skills (+.48), and computer/technical skills (+.68). This fits neatly with the skills stressed in this class: coding and computer-design skills and the ability to work in groups to solve a problem, which necessitates communication skills. Students also had to mentor local K-12 students in the lab, which is the topic of a different paper. We note this because it likely increased their communication skills.

Overall, our results are robust and consistent, showing that the addition of this course to undergraduate curricula is useful to students, both objectively in terms of knowledge and skills in AM and subjectively in terms of their own self-assessments. We have collated our lab manuals and lectures in a course website that is publicly accessible and welcome emails from interested parties.

Appendix: Content Knowledge and Attitudinal Assessment

(1) Which kinds of materials can be fabricated by additive manufacturing processes (more than one answer)?

(A) Metals (B) Ceramics (C) Plastics (D) Composites

(2) 3D printable models may be created with a computer-aided design (CAD) package, and __________ is one of the most common file types that all the 3D printers can read and print.

(A) .sldftp (B) .dwg (C) .stl (D) .cad

(3) Which one of following processes used filament as starting material (feedstock)?

(A) Fused Deposition Modeling (FDM) (B) Selective Laser Melting (SLM)
(C) Stereolithography (SLA) (D) Laser Engineered Net Shaping (LENS)

(4) Which one of following processes would not be used in additive manufacturing fabrication?

(A) Extrusion (B) Fusion welding
(C) Polymerization (D) Machining

(5) Which of the following processes has the lowest unit manufacturing cost?

(A) Fused Deposition Modeling (FDM) (B) Selective Laser Melting (SLM)
(C) Stereolithography (SLA) (D) Laser Engineered Net Shaping (LENS)

(6) You can recycle many plastic containers and extrude them into reels of filament used on Fused Deposition Modeling (FDM) 3D printers. These plastics are __________.

(A) thermoplastics (B) thermosets (C) photopolymers

(7) In 2015, the FAA cleared the first 3D printed part to fly in a commercial jet engine from GE. It is the housing for the compressor inlet temperature sensor as shown in this right figure. By layering powered metals that are melted and fused together through a process known as __________ the pieces are welded together as one and come out five times stronger than its predecessor.

(A) Selective Laser Melting (SLM)

(B) Fused Deposition Modeling (FDM)

(C) Stereolithography (SLA)

(D) Laser Engineered Net Shaping (LENS)

(8) Which of the following additive manufacturing solutions applies an ultraviolet light to a liquid polymer to change it into solid plastic?

(A) Selective Laser Melting (SLM) (B) Fused Deposition Modeling (FDM)

(C) Stereolithography (SLA) (D) Laser Engineered Net Shaping (LENS)

(9) Post processing ______________ be used after AM fabrication?

(A) has to (B) doesn’t have to

(10) Generally speaking, the AM fabricated parts have better surface roughness than machined parts. Please judge this statement.

(A) True (B) False

(11) In your opinion, what is additive manufacturing or 3D printing?

(12) Please talk about how the part would be built from 3D model to 3D part in an additive manufacturing process?

(13) Discuss the current benefits and limitations of 3D printing; give examples of areas where 3D printing is becoming mainstream.

(14) Current AM/3D printing technologies all build a part in a layer-by-layer fashion. Do you think it is the perfect way to build every part? What can you imagine as a "true AM/3D printing technology", why it is better than the state-of-the-art now?

(15) Biofabrication is strongly reliant on 3D printing to accurately place cells, matrix and materials in position for tissue engineering. These constructs can be used as testing systems for new drug discovery, understanding cell biology and for replacing tissues and organs that are damaged through injury or disease. As you can imaging, bones, tissues, and organs, especially for a specific individual, cannot be drawn easily using an engineering CAD package, can you think of any approach to generate these digitalized and individualized 3D printable files?

(16) Please circle your department and institute.

I. (A) ME (B) IE or IMSE (C) Others ____________________ Please list.

(17) What is your classification? Please circle: Freshman Sophomore Junior Senior

(18) What is your sex? ________

(19) What is your race? __________

(20) Are you a first-generation college student? Yes No

(21) Please rank each of the skills listed below in order of how important you believe they are for an engineer to have (1 is least important, 5 is most important). Then, on the same 1-5 scale, rate yourself on how well developed you are in that skill (1 is not developed at all, 5 is fully developed).

	Importance for Engineering	Self-Development Score	Have you improved in this skill since the beginning of the semester? Y/N
Communication Skills, including Listening Skills			
Ability to Work Effectively in a Team/Group			
Math and Science Skills and Knowledge (not including computer skills)			
Ability to be Creative			
Problem Solving Skills			
Leadership and Management Skills			
Computer Skills (including programming and modeling)			
Technical Skills and Knowledge			
Time Management Skills (including punctuality)			
Analytical Skills			
Orderliness and Organizational Skills			
Attention to Detail			

Appendix B:

COMPILED DATA (2018-2021):

Content Knowledge Statistics:

Table 1: Content Knowledge Averages and Differences at Times 1 and 2, by University

	Time 1	Time 2	Change (of matched pairs)
TTU	$\underline{X}$=16.1	$\underline{X}$ = 33.2	17.1***
KSU	$\underline{X}$=15.3	$\underline{X}$=31.2	15.9***
CSUN	$\underline{X}$=13.9	$\underline{X}$=28.78	14.88***
Aggregate Total	**15.1**	**31.06**	**15.96**

* p<.10 ** p<.05 ***p<.01

Table 2: Content Knowledge Averages and Differences at Times 1 and 2, by Demographics

	Time 1	Time 2	Change (of matched pairs)
Males (N=143)	$\underline{X}$= 19.4	$\underline{X}$ = 32.1	+12.7***
Females (N=71)	$\underline{X}$ = 17.7	$\underline{X}$ = 32.6	+14.9***
White Students (N=121)	$\underline{X}$ = 20.1	$\underline{X}$ = 35.2	+15.1***
Non-white Students (N=92)	$\underline{X}$ = 16.7	$\underline{X}$ = 33.6	+16.9**
First Generation College Students	$\underline{X}$ =18.1	$\underline{X}$ = 31.7	+13.6***
Non-First Generation College Students	$\underline{X}$ = 18.6	$\underline{X}$ = 32.47	+13.87***

* p<.1 ** p<.05 ***p<.01

Self-Efficacy Statistics:

SELF EFFICACY RATINGS		Time 1 N=11	Time 2 N=11	Change
Job Related Skills	Analytical Skills	4.00	3.67	-0.33
	Computer/Technical Skills	2.64 | 3.55 | 3.06	3.32 | 3.73 | 3.56	**0.68**** | 0.18 | **0.5****
	Math/Science Skills	3.74	3.82	0.08
	Creativity	3.78	3.54	-0.24
	Problem Solving	4.12	4.48	0.36
Interpersonal Related Skills	Leadership	4.18	4.27	0.09
	Communication	3.91	4.39	**0.48****
	Teamwork	4.2	4.8	**0.6****
Life and/or Professional Skills	Time Management	3.64	3.55	-0.09

* p<.10 ** p<.05 ***p<.01

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