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The Broader Impacts of an Additive Manufacturing Course at Three Large Universities

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The Broader Impacts of an Additive Manufacturing Course at Three Large Universities

WIP: Implementation and Assessment of Project

Abstract: This paper documents the effects of an additive manufacturing course on two sets of students: (1) the undergraduates who took the course and (2) the middle and high school students who visited our labs. At the time of the conference, nine semesters of data (three years at three schools) will have been collected, as well as data from the middle and high school students who visited our labs. Overall, our research questions were: (1) what is the effect of this course on the content knowledge of (a) enrolled undergraduates and (b) middle and high school students? And (2) what is the effect of this course on the attitudes towards engineering and self-efficacy in engineering for (a) enrolled undergraduates and (b) middle and high school students? To determine the answers, our longitudinal matched-pairs data collection was conducted. In short, as measured by t-test, all students improved on content knowledge ($p<.01$), but female students improved slightly more than male students (+9.89 versus +9.01, respectively). Undergraduates did not change their minds about the factors that are important in engineering, although they did significantly change their self-efficacy ratings in some skills because of the course. In particular, undergraduates rated themselves higher in teamwork, creativity, and technical skills, which reflect the content and focus of the course. Additionally, we brought multiple field trips of middle and high school students into our labs for outreach. Using a simplified version of the metric described above, we can see that all students improved on content knowledge.

Introduction and Background:

Additive manufacturing is a class of manufacturing processes where material is deposited in a layer-by-layer fashion to fabricate a 3D part directly from CAD model (ASTM) [1-5]. Additive manufacturing (AM), or 3D printing, has revolutionized and redefined how products are designed, manufactured, distributed and utilized for many industries around the world. AM is one of the pillars for Industry 4.0. It has the power to transform the digital-physical interface for product design, development, and manufacturing. The global value of AM products and services is expected to grow considerably from \$ 4 billion in 2015 to \$ 10.8 billion in 2021 [6]. The fast-evolving AM technologies and market in the global Industry 4.0 background is creating a skill shortage in workforce pipeline and knowledge gap in related education and training. This requires the creation of courses and other educational activities to equip students and faculty with this new expertise to meet the increasing demand for engineers, designers, and educators in AM.

AM is attracting more and more attention and is under intensive investigations for the fabrication of multiple types of engineering materials, including metals, ceramics, composites, and plastic, due to the capability of fabrication with these materials. AM is becoming popular in producing an impressive array of products for aerospace industry due to the shortened cycle time, shortened time to market, part remanufacturing, the improved product performance, and on-demand product solutions; the automotive industry because of design freedom, the fast cycle time from design to production, on-demand manufacturing, less material consumption, added features to increase function and speed, the improved package design to reduce drag; orthopedic industry due to the flexible and efficient production and design freedom; etc. The continuously increased growth of AM applications will generate significant impacts on the manufacturing industries, U.S. economy, and society in general.

However, despite AM's increasing importance to the U.S. economy, we found (via of a survey of approximately 60 other colleges of engineering) that almost no universities have a permanent undergraduate course on it. Thus, we have created and implemented such a course at our universities with NSF support (grant number redacted). This paper documents the effects of an additive manufacturing course on two discrete sets of students: (1) the undergraduates who took the course and (2) the middle and high school students who visited our labs. This course was designed to teach engineering undergraduates the principles of additive manufacturing and was supported by funds from NSF IUSE grant 1712311. It has been simultaneously run during the spring semester for the past three years at Texas Tech University (a Carnegie high research productivity and Hispanic Serving Institution), Kansas State University (a Carnegie high research productivity and land grant school), and California State University, Northridge (a public state school that focuses on teaching first-generation and other underprivileged students). Currently, nine semesters of data (three years at three schools) have been collected, as well as data from the middle and high school students who visited our labs.

Overall, our research questions were: (1) what is the effect of this course on the content knowledge of (a) enrolled undergraduates and (b) middle and high school students? And (2) what is the effect of this course on the attitudes towards engineering and self-efficacy in engineering for (a) enrolled undergraduates and (b) middle and high school students? We were also able to decompose the student groups into sub-groups by race, gender, first-generation college student status, major, and between universities to determine if there are differences in effects between those categories.

Background on the Course:

The course is in a weekly lecture then lab format to help students understand the fundamentals and theoretical knowledge from an expert and then engage with and apply that knowledge in a lab setting with the actual 3D printers. It is a smaller, upper-division election with enrollments (in each section) of about 20 students per university per year, so students get a great deal of contact and instructional time with the professor. In content, the course focuses on three types of additive manufacturing processes: liquid-based, powder-based, and extrusion-based, as well as gaining practical knowledge and experience with common AM materials like metals and alloys, polymers, ceramics, and other composite materials. The objectives of the course include:

1. Learn about the fundamental principles and changing technologies of additive manufacturing
2. Create designs of objects and/or parts using commercial software
3. Digitize free-form geometry
4. Be able to describe and assess the applications, capabilities, procedures, and advantages/disadvantages of AM
5. Define the criteria necessary for different AM processes
6. Apply those criteria to select the appropriate process
7. Have practical experience in different areas of AM, including the ability to solve common problems
8. Conduct outreach to local schools.

We are in the process of publishing a textbook based on the content, procedures, and learning outcomes of the lab projects, including detailed notes for students and professors as to how to conduct these labs in their own classrooms. This is designed to be a complement to other textbooks based on content knowledge of additive manufacturing. The course is a junior-level class with a limit of 25 students and meets for three hours a week. It is designed to start students in the lab almost immediately, after a brief set of lectures that take place only in the classroom learning about some of the principles of AM in addition with safety precautions. The rest of the semester is designed to have students learn about principles and problems, then immediately begin applying that knowledge and engaging problem-solving and critical-thinking skills while doing the labs.

The final objective – outreach – is based on the field trips that local middle and high school students took to our labs to learn about additive manufacturing from the undergraduate students. Undergraduates gave presentations in groups about different topics in AM, including how to create designs, how to digitize those designs, and how to program the actual machines. The middle and high school students were then paired with an undergraduate mentor for hands-on experience. The middle school students had single day field trips, while the high school students returned twice over the course of two weeks. More information about assessment of these trips can be found below in the methods section.

Methods:

Data Collection and Analysis:

To be able to assess the effects of this course on both undergraduates and on the middle and high school students with whom they interacted, we need two datapoints: Time 1 (at the beginning of the semester or field trip) and Time 2 (at the end of the semester or field trip). The assessment metric was comprised of two parts: a content knowledge assessment and an attitudinal assessment. The former was tailored to the academic level of the respondents. Specifically, the undergraduates had ten multiple choice questions (each worth two points) and five essays (each worth five points), written for upper-level engineering students. The 6th-12th graders had five essay questions that assumed no prior knowledge of engineering. This was blinded and then "graded" by the three engineering professors associated with the project. Because of ethical guidelines, no actual course grade was attached to this assessment. Students were told to "do their best" in order to determine results.

The latter metric, the attitudinal metric, consisted of a previously validated Engineering Skills Assessment that was inductively developed and tested for validity on engineering undergraduates [7-8]. This metric and the undergraduate content knowledge one can be found in Appendix A. The attitudinal metric also contains questions about year of study, major, and demographics including race, gender, and first-generation college student status. The results from 2020 are currently being collected and will be available at the conference in June. The data presented in this paper are from the spring 2019 semester and collected identically. To determine whether there was any content knowledge growth or attitudinal change between Times 1 and 2, a paired samples T-test was used. This also allowed us to measure change in sub-groups including by race, gender, major, and first-generation college student status. Overall, we had 55 matched pairs (those with data at Time 1 and Time 2), with 16 at Texas Tech, 20 at Kansas State, and 19 at CSUN. One to two students per university were present at Time 1 but not Time 2, likely because they dropped the class. They are not included in the data analysis.

Results:

Undergraduates:

The tables of results can be seen in Appendix B below. Table 1: Content Knowledge Averages shows the difference over the course of the spring 2019 semester by university and overall. We can see that all students, irrespective of university, increased significantly by 9.1267 points on a 0-45 point scale ($p<.01$) in content knowledge. There was no statistical difference between TTU and KSU, but CSUN had a smaller increase (albeit still statistically significant [$p<.01$] one) from Time 1 to Time 2. We attribute this smaller increase to the lower socioeconomic student population found in CSUN, but it’s an area of concern that we are actively observing in the spring 2020 semester.

These results can also be broken down into self-identified sub-groups by gender, major, race, and first-generation college student status. Again, we can see that all subgroups experienced statistically significant growth over the course of the semester ($p<.01$). Table 2: Content Knowledge Averages…by Demographics shows the specific starting and ending numbers. Overall, we see that men (N=41) and women (N=14) experienced the same growth, with approximately the same starting and ending averages (no statistical difference was observed between men and women at Time 1 or Time 2).

This was, however, not the case when the groups were broken down by major. Industrial engineering (IE) was the largest major in our sample (N=31), with mechanical engineering (ME) a distant second (N=11). There were other engineering majors present in the sample, but no single major was large enough to form its own group, thus they were left out of this between-major analysis. There was a statistical difference at Time 1 ($p<.05$), with ME averaging higher than IE. This difference actually reversed itself at Time 2, where IE outpaced ME by 1.49 points, although this difference was not statistically significant. Both groups experienced a statistically significant growth ($p<.01$).

There were 31 white students and 14 students who identified as something other than white on the surveys. Due to low numbers in the non-white group, we collapsed our racial categories into white and non-white for statistical analyses. Interestingly, there was no statistical difference between the groups' scores at Time 1. There was a small statistical difference between the groups at Time 2 (at the $p<.1$ level, not $p<.05$)), with the white students gaining 10.55 points over the course of the semester and the non-whites gaining 8.93 points. The same pattern was found in first-generation college students (N=11) and non-first-generation college students (N=35), in that there was no statistical difference between the groups at Time 1, but the non-first-generation college students increased slightly more (+10.4 points) than the first-generation college students (+8.55). Both groups increased at statistically significant levels ($p<.01$), and the difference of the increase between the two groups was also statistically significant, albeit barely at the $p<.1$ level, not $p<.05$.

The attitudinal shifts that occurred during the course of the semester showed an interesting and similar pattern to results from the spring 2018 semester. Table 3 shows what respondents thought was important to engineering (as well as change during the semester) and Table 4 shows their own self-rating on those skills (as well as change during the semester). There are different total numbers for the content assessment and perceptual assessment because some students chose not to complete both. These item constructs (Job Related Skills, Interpersonal Related Skills, and Life/Professional Skills) were first grouped according to inductive analysis from qualitative data collection among engineering undergraduates in an unrelated project [7]. The constructs were then validated via an exploratory factor analysis and internal consistency metrics that replicated the findings of the qualitative analysis [8]. Overall, students did not appear to change their minds about what is important in engineering, although they did rate analytical skills and time management as less important at Time 2 than at Time 1 (p<.1). The largest shift can be seen in students' self-efficacy levels. All three constructs showed statistically significant gains (p<.01) and nine of the 11 individual skills showed statistically significant gains. This is promising because high levels of belief in self-efficacy correlate with increase tenure in engineering and career persistence, particularly in women and students of color. The largest statistically significant gains were found in teamwork, creativity, and technical skills, which reflect the content and instructional activities (group work, practice on AM machines, and digitizing objects) of the course. Students were not shown their original scores at Time 2 data collection in order to remove bias.

Outreach – Effects on Middle and High School Students

Table 5 shows content knowledge differences at the beginning and at the end of the field trips to our labs. We can see that, as expected, middle schoolers generally perform worse than high schoolers, both at Time 1 and Time 2. This is on the same 15-point scale. This is likely because of the age difference between the two groups, but also because the high school field trips were longer and repeated, as appropriate for age levels. Coincidentally, both groups experienced a knowledge growth of 5.16 points, which was statistically significant (p<.01). Verbally, students expressed to us that they were interested and encouraged by the field trips, saying that they didn't realize that "3D printing could be used for so many things" and "it's actually easier than I thought. Maybe I'll pursue this in college."

Conclusion:

Overall, we can see that the undergraduates enrolled in this course were able to improve at significant levels in knowledge over the course of the semester, regardless of university affiliation or demographic factors like race, gender, or first-generation college student status. This was also true for the middle and high school students who came to visit our labs for field trips. Anecdotally, the undergraduates highly enjoyed mentoring the younger students, and found that teaching AM skills to a younger generation was both personally fulfilling and helped to cement those foundational skills in their own minds. We found that this course improved knowledge of AM, as well as professional skills like teamwork, creativity, and computer skills, thus setting our undergraduates up for a better trajectory in their later engineering careers.

Appendix A: 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:

Content Knowledge Statistics:

Table 1: Content Knowledge Averages and Differences at Times 1 and 2, by University, in 2019

	Time 1	Time 2	Change (of matched pairs)
TTU	$\bar{X}$=14.625	$\bar{X} = 25.56$	16 matched pairs, +10.935***
KSU	$\bar{X}$ =15.8	$\bar{X}$=27.5	20 matched pairs, +11.7***
CSUN	$\bar{X}$ = 13.05	$\bar{X}$=17.79	19 matched pairs, +4.74***
Aggregate Total	**$\bar{X}$ =14.49**	**$\bar{X} = 23.61$**	**55 matched pairs, +9.1267*** **

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

Table 2: Content Knowledge Averages and Differences at Times 1 and 2, by Demographics, in 2019

	Time 1	Time 2	Change (of matched pairs)
Males (N= 41)	$\bar{X}$= 14.76	$\bar{X}$ = 23.78	+9.02***
Females (N=14)	$\bar{X}$ = 13.79	$\bar{X}$ = 23	+9.21***
Industrial Engineering (N= 31)	$\bar{X}$ = 15	$\bar{X}$ = 26.13	+11.13***
Mechanical Engineering (N=11)	$\bar{X} = 17.55$	$\bar{X} = 24.64$	+7.1***
White Students (N=31)	$\bar{X}$ = 15.58	$\bar{X}$ = 26.13	+10.55***
Non-white Students (N= 14)	$\bar{X}$ = 15.29	$\bar{X}$ = 24.21	+8.93***
First Generation College Students (N=11)	$\bar{X} = 14.64$	$\bar{X} = 23.18$	+8.55***
Non-First Generation College Students (N=35)	$\bar{X}$ = 15.49	$\bar{X} = 25.89$	+10.4***

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

Perceptual and Self-Efficacy Statistics:

Table 3: IMPORTANCE TO ENGINEERING		Time 1 N=39	Time 2 N=39	Change
Job Related Skills	Analytical Skills	4.33	4.07	**-.26***
	Computer/Technical Skills	3.85	3.82	-.03
	Math/Science Skills	4.21	4.28	.01
	Creativity	4.15	4.03	-.13
	Problem Solving	4.97	4.82	-.15
	Overall Job Related	*4.302*	*4.204*	*-.56*
Interpersonal Related Skills	Leadership	3.95	4	.05
	Communication	4.69	4.59	-.1
	Teamwork	4.77	4.74	-.03
	Overall Interpersonal	*4.47*	*4.44*	*-.03*
Life and/or Professional Skills	Time Management	4.54	4.26	**-.28***
	Orderliness and Organizational Skills	3.92	3.77	-.15
	Attention to Detail	4.49	4.33	-.15
	Overall Life/Professional	*4.32*	*4.12*	*-.2*

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

Table 4: SELF EFFICACY RATINGS		Time 1 N=39	Time 2 N=39	Change
Job Related Skills	Analytical Skills	3.54	3.74	**.21***
	Computer/Technical Skills	2.87	3.82	**.95*****
	Math/Science Skills	3.72	3.81	.09
	Creativity	3.33	3.97	**.64*****
	Problem Solving	3.82	4.33	**.51*****
	Overall Job Related	*3.46*	*3.93*	***.47******
Interpersonal Related Skills	Leadership	3.64	3.92	**.28****
	Communication	3.97	4.04	.06
	Teamwork	3.87	4.45	**.58*****
	Overall Interpersonal	*3.83*	*4.14*	***.31******
Life and/or Professional Skills	Time Management	3.56	3.64	.08
	Orderliness and Organizational Skills	3.38	3.82	**.44*****
	Attention to Detail	3.67	4.08	**.41****
	Overall Life/Professional	*3.54*	*3.85*	***.31*****

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

Outreach and Engagement with Middle and High School Students

Table 5: Content Knowledge Averages and Differences at Times 1 and 2, by Middle and High School Outreach Participants

	Time 1	Time 2	Change (of matched pairs)
Middle School	$\bar{X}$=2.15	$\bar{X} = 5.41$	41 matched pairs, +5.16***
High School	$\bar{X}$=6.09	$\bar{X} = 11.25$	22 matched pairs, +5.16***
Aggregate Total	$\boldsymbol{\bar{X} = 4.12}$	$\boldsymbol{\bar{X} = 8.33}$	

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

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