A Systematic Review of Additive Manufacturing Education: Towards Engineering Education Research in AM

Abstract: Additive Manufacturing (AM) has garnered a lot of interest from industries, government agencies, and institutions around the globe. Manufacturers are relying on this technology to significantly re-invent product design and manufacturing cycles. The third industrial revolution has already begun, and as such, workforce development and education is essential. Additive Manufacturing technologies in particular offer significant technological development, but require agile specialists to embrace manufacturing technologies. Master's degree-level education is therefore essential to developing this specialized workforce. Since Additive Manufacturing is inherently an interdisciplinary avenue, the AM workforce requires skillsets crossing all engineering backgrounds. Inculcating AM education at the undergraduate, graduate, and professional levels could be a thought catalyst for engineering majors from diverse backgrounds and enable collaboration within different engineering sciences. The purpose of this paper is to review literature surrounding of additive manufacturing education, with particular focus on graduate education as a venue to educate a specialized expert workforce. Further, we identify several key areas where foundational engineering education research can help to highlight and shape AM as an emergent field, including opportunities for learning science, online education, and workforce development; the development of interdisciplinary and agile expertise; and considering belongingness, diversity, and inclusion in Additive Manufacturing.

Introduction

Additive manufacturing (AM) is a set of processes by which physical objects are made from digital files generated by computer-aided design software. The term encompasses seven different technologies, as per ASTM nomenclature [1], powder bed fusion, material jetting, directed energy deposition, binder jetting, vat photo polymerization, material extrusion and sheet lamination. These technologies use a variety of feedstock materials such as polymers, metals, ceramics, and concrete by systematically depositing layer upon layer to create a near net shape of the final part required. As opposed to traditional machining techniques like CNC, milling, machining, in AM, material is *added* instead of removed from a block or a billet. AM developed out of rapid prototyping technologies, invented thirty years ago. The pace of evolution of the technology to additive manufacturing is noteworthy caused mainly by quality and value addition which Additive manufacturing proposes in the product development process: shorter lead times, less waste, and competitive products. With the emergence and proliferation of the technology, there is an increased demand of workforce which can understand principles of Additive manufacturing processes and optimally apply it to solve real life world problems.

This paper investigates existing efforts in Additive manufacturing education and its implications in engineering education research. Inferences from the review can provide a springboard for educators and researchers in engineering education to address the following questions:

1. How can we bridge the gap between the ever increasing demands of an industrial workforce which could understand Additive Manufacturing and the current state of the system?
2. How can Engineering Education research facilitate the development of the field of Additive Manufacturing?

The Need for More Talent in Additive Manufacturing

The emergence of additive manufacturing has also opened up new possibilities in material science, design and fabrication of complex structures which were nearly impossible to make with conventional manufacturing processes. Due to the widespread of this technology in a short time, the industry is currently facing challenges with lack of design for AM principles, process guidelines and standardization of best practices [2]. As per Deloitte's review report, the global 3D printing industry is poised to grow from $12.8 billion in revenue in 2018 and it is expected to exceed $21 billion by 2020 [3].With prompt adoption of this technology in the industry, the demand for workforce equipped with AM skills is poised to increase exponentially. The diverse field of AM sciences requires a combination of engineering and soft skills for a successful career path. Moreover, the key to success of AM is its variety of applications such as medical, automotive, aerospace, art, and construction applications, which requires domain knowledge expertise coupled with appreciation of AM sciences. Such unique combination of skills makes the workforce required in Additive manufacturing recruitment - distinctive and unorthodox.

Accelerating efforts towards growing the talent pool capable of learning and applying Additive manufacturing principles is correspondingly essential as increasing awareness and adoption of the technology. AM is a major component of the third industrial revolution which could create more job opportunities in developed nations. Given that automation capabilities play a major role in shaping Industry 4.0, digital factories of the future would not necessarily be labor intensive. AM could be the United States' answer to labor-intensive manufacturing hubs like China, India and Vietnam and can help decentralize manufacturing.

The talent gap is not only restricted to AM, but manufacturing overall. As per the latest Society of Manufacturing Engineers report, nine of ten manufacturers have difficulty recruiting desired talent. There is no doubt that to speed up the adoption of AM and make it a widely adopted manufacturing process, the question of the current system's readiness to absorb the transition has to be addressed with adequate quantum of skilled workforce. The "2009 Roadmap for Additive Manufacturing" [4] suggests development of university courses and educational materials at the undergraduate and graduate level. The need to develop workforce for AM is one of the core emphasis of the Roadmap, since unfamiliarity with AM capabilities is seen as a major barrier to adoption of AM. Similarly, these problems can be identified as key obstacles to generate talent in Additive Manufacturing: (1) The Millennial generation's negative perception of the manufacturing industry; (2) Lack of interdisciplinary STEM skills; and (3) Lack of practical hands-on or on-the-job training.

Such an acute shortage of human labor calls for a systematic plan to address the workforce shortage. In an effort to address the problem, The National Science Foundation held a workshop in 2015 to discuss the educational needs to equip the industry and academic system for Additive manufacturing. A unique cohort of individuals from academia, industry, and government formulated the way forward to inculcate AM in education at all levels. As per the NSF workshop report for additive manufacturing education [5], the following key areas were identified which helps further dissect the problem :

a) AM processes and material relationships
b) Fundamental knowledge of material sciences and manufacturing processes
c) Professional acumen for critical thinking and problem solving
d) Design for Additive manufacturing practices
e) Cross functional teaming and ideation techniques for seeding creativity.

While many of these key areas are technical in nature, many also are inherently human, related to foundational questions that engineering education research is working to tackle. However, to date, the rigorous engineering education research community has not yet launched efforts to study creativity, design thinking, teaming, or problem solving in the context of Additive Manufacturing either with respect to students or practicing engineers. The following sections review educational efforts to date, summarize main directions for AM education, and promote areas for inclusion of engineering education research within the emergence of AM education.

Chronological Review of AM Education Efforts

The literature on Additive Manufacturing Education is scarce, likely due to the recent emergence of both the disciplines of AM and Engineering Education. The first effort and suggestion of including Rapid Prototyping into the engineering curriculum was proposed by Bohn in 1997 [6]. The emphasis on the need for integrating aggressive prototyping into the design development cycle was highlighted in his work. He asserted that the engineering curriculum at that time did not address the importance of prototyping and was less practiced in homework, projects, or laboratories. An experiment was conducted with senior design students through an iterative design-fabrication-redesign-fabrication sequence to enable hands-on experience on desktop-level manufacturing equipment. His work strongly asserts the need to include practical training while including design-intensive prototyping courses. During the initial phases, universities do not need to invest in commercial-level equipment, since desktop machines could provide students with useful insights for basic understanding of processes. The same experimental introduction activity can be further pursued in a modern design or prototyping class to study the effects of availability of prototyping equipment in student's ideation and process.

Anecdotally, instructors lament that engineering design is 'hard to learn and harder to teach.' There has been a rising interest in 'Design for additive manufacturing' (DfAM) education within the past decade. DfAM is a thought process where existing and new design principles are consolidated to develop a framework which could optimally make use of the design freedom served by Additive manufacturing. Williams and Seepersad [7] attempted to address the gap in AM education by developing an undergraduate/graduate course to educate students on the underlying science of AM processes using principles of DfAM. The authors used both problem-based and project-based methods for providing students with a hands-on experience with Additive manufacturing technologies. The findings from their experimental work posit that introducing students to challenging design activities can increase their learning quotient and promote creativity. The decision making process adopted by students could have been provided for a better overview and repeatability of the experiment. Engineering educators can use similar techniques in early years of academia to introduce design activities to expose students to the world of design and cultivate interest in manufacturing education where design is an integral part of the process.

Minetola et al. [8] presented a survey on the impact of additive manufacturing on engineering education. The consequences from the survey present that there is an increase in the ease of learning, perceived interest and motivation amongst mechanical engineering graduate students after being able to get hands-on access to AM technologies. Such findings could provide a basis for engineering professoriate to build a case for Additive Manufacturing education. The paper also suggests that an early exposure of future generation designers to AM techniques can aid in the development of a "think-additive" style to product design. Inferences from this paper could be used as cases for universities to explore the option of including AM education in freshman and sophomore curriculum.

Concepts like BYOD (bring your own devices) and DIY (do-it yourself) are proven to be useful for hands-on student led projects where they use open-source software and hardware to create projects and assignments. Exposing students to open source architecture could lead them to be part of "makerspaces" and DIY clubs thereby enhancing their manufacturing quotient. Chong et al. [9] proposed a blended learning model for inculcating skills required for Industry 4.0 readiness, including additive manufacturing using traditional methods, online learning, and flipped classroom approaches, with an emphasis on computer aided drafting (CAD) skills, which are imperative in 3D printing design. Chong's work reveals that most engineering programs in their university are not ready for the transition to 3D printing-focused curriculum because of the paucity of courses that incorporate Industry 4.0 elements (in Chong's study, 28% of courses). Similarly, the challenge of inadequate resources for training and implementation of Additive manufacturing related academic activities are major concerns for universities. Radharamanan [10] recently highlighted the significance of including an Additive manufacturing course as a part of the manufacturing curriculum, detailing the development and implementation of a senior-level elective course in Additive Manufacturing. He noted that the students needed additional training in CAD and reverse engineering skills with the help of hands-on projects, a suggestion that likely applies to other academic institutions adopting AM education curricula.

Current Progress: The Advent of AM Graduate Programs

Graduate programs dedicated to Additive Manufacturing have seen a measured growth in the last three years. The Pennsylvania State University's Masters of Science in Additive manufacturing and design program is considered to be the first of its kind in the USA. The course offers an online option as well for professionals intending to continue education. The students find benefit in lectures from industry experts from Center of Innovative Materials Processing through direct digital deposition (CIMP 3D) and Applied Research Laboratory [13]. The University of Maryland also offers a graduate program in Additive manufacturing and students use resources from the Makerbot Innovation Center on campus [14]. Carnegie Mellon University has recently announced a two-semester long Master of Science (MS) in Additive manufacturing program [15]. In the United Kingdom, Nottingham University, University of Sheffield, and Derby University offer a graduate level course in Additive manufacturing. The Universitat Politècnica de Catalunya in Barcelona, Spain offers a Design and Engineering for Additive manufacturing master's program with collaboration from industry experts [16].

In addition to these formal degrees there are several initiatives for online certification and certificate programs. MIT offers a 12-week online course [17] on the fundamentals, applications and implications of 3D printing for design and manufacturing which has garnered interest from industry professionals. Management consulting firms like Deloitte, PWC, and Ernst & Young are offering tailor-made courses for their clients to foster adoption of Additive manufacturing. Dedicated courses in Additive manufacturing are emerging, but the demand from the industry surpasses the existing supply. Therefore, more universities can include dedicated AM degrees into their curriculum coupled with research opportunities to develop AM engineers of the future.

Developing a Framework for an AM Curriculum Leveraging Engineering Education Research

In recent reports, the following issues served as potential road blocks for universities to inculcate Additive manufacturing into their curriculum[13]:

1) Expensive initial costs of software and hardware
2) Rapidly evolving technology makes defining the content tricky (DFAM)
3) Definition of skillsets required for AM engineers
4) Interdisciplinary skillsets for AM professionals to "connect the dots" between disciplines

The pace of innovation in Additive Manufacturing makes it tricky for educational institutions to keep up. One way to address this issue could be by conducting 'Knowledge update sessions' within the ecosystem where students and educators share the latest news in the industry thereby creating a co-learning environment. Also, frequent technology transfer sessions could be conducted by AM companies on campus. The NSF workshop on AM suggested that an AM curriculum should provide the understanding of both traditional and additive processes which would help students to make process selection decisions. Design for AM and the process-material property structure relationships can also be included [5]. The skillsets required for an AM engineer would be a broad topic to address owing to the breadth of industries which concern Additive manufacturing. Some of the main areas which could lead to holistic content creation can be described from Figure 1.

Of course, there are limitations to incorporating authentic AM education, one of which is the high initial costs of procuring AM machines and software. This issue could be mitigated by industry – academia collaboration. Many original equipment manufacturers prefer an academic partner as a third eye to assess their products capabilities through unbiased and independent research. Some public and private universities like Penn State and Arizona State University have already taken advantage of this situation. National Science Foundation's Rapid Tech program aims to aid adoption of AM within the industry and educators [7]. America Makes is accelerating the adoption of additive manufacturing technologies in the United States to increase domestic manufacturing competitiveness. This public-private partnership is the nation's leading partner in AM research, discovery, creation and innovation and offers apprenticeships, co-ops, and educational facilities to promote 3D-printing and Additive manufacturing education [18].

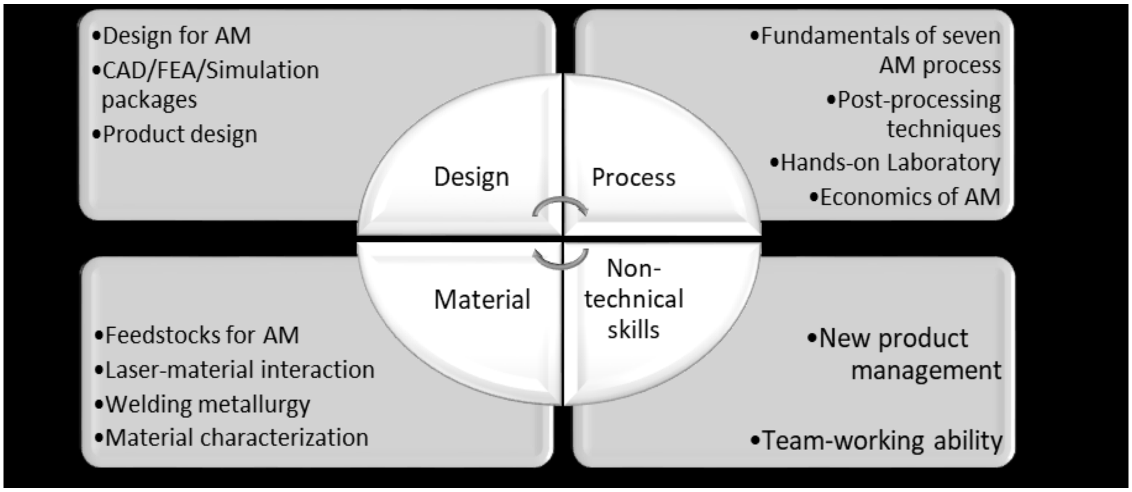

Figure 1. Synthesis of Desired AM Curriculum Content

Within these curricular suggestions, we propose that the engineering education research community begin to employ the context of AM education to consider foundational topics such as cognition, learning, diversity and inclusion, and workforce development. We see several areas where engineering education research can be applied, tested, and created. While we see great opportunity for studying foundational engineering education processes in graduate students specializing in AM, these topics can be extended to specialized undergraduate courses.

1. *Opportunities for learning science, online education, and workforce development.* While a great deal of research has been accomplished in active learning and best practices for undergraduate engineering, very little classroom research has been accomplished at the graduate level, especially confounded by the interdisciplinary nature of AM. Similarly, while design thinking research is well established as a topic of specialty in engineering education, the EER community has yet to apply rigorous design thinking methods to Additive manufacturing, only beginning to be explored. A recent experiment from Prabhu et al [11] explored the characteristics of DFAM education on the cognitive essence of student's creativity. The study used possible combinations of no, restrictive, and dual DFAM principles and concluded that students learning the overall aspects of DFAM improve their self-efficacy. Another paper from the group [12] investigates the importance of timing in effectiveness of DFAM education. An important observation is made that introducing DFAM concepts at an earlier stage improves students perceiving utility. A valuable take away from their work is that introducing Additive manufacturing education at an early-career level proves to be advantageous and aids in effective learning. Additional potential overarching research questions the Engineering Education research community could contribute to solving include
   - How can online, remote, or virtual educational environments be designed to harness best practices in active learning developed for residential classrooms?
   - How can best practices developed for undergraduate students be adapted to meet the needs of adult learners?

- How do practicing manufacturers "unlearn" methods for traditional manufacturing and adapt to changing advantages and limitations for additive manufacturing?
- How can large-scale efforts for workforce development be translated to target different workforce levels?

2. *Investigation of the development of interdisciplinary and agile expertise.* The context of AM as an inherently interdisciplinary environment merging several engineering sciences and extended to various applications (e.g., medical, automotive, aerospace) requires that we have a better understanding of how graduate students, researchers, and leading experts develop interdisciplinary expertise and learn to work on diverse teams to conduct team research. Further research needs to be performed to identify differences and effects of engagement on benchmarking practices on fixation, creativity and designer cognitive workload. Research questions of interest to engineering education researchers might include
    - How do experts and graduate students develop interdisciplinary expertise?
    - What experiences are necessary to promote transfer of principles from more formal educational opportunities to hands-on educational or practice activities?
    - How do experts integrate multidisciplinary knowledge in diverse teaming experiences, and how can these skills and practices be translated into authentic practice experiences in the graduate (or undergraduate) curriculum?
    - How do theories of distributed cognition and transfer apply in cross-disciplinary, interdisciplinary, and multidisciplinary teams of experts in graduate school and in practitioners?
    - How do research topics like ideation, fixation, prototyping, and communication manifest in Additive Manufacturing?

3. *Considering belongingness, diversity, and inclusion in Additive Manufacturing.* The emergence of AM as an expertise has inherent issues with accessibility, since 3D printers and materials are expensive and not typically available to all universities. There is an element of trendiness and exclusion to the formal Additive Manufacturing research community. Manufacturing as a discipline, too, holds considerable stereotypes of being highly male dominated, and comprised of manufacturers from other generations that may seem exclusionary to women or engineers from traditionally underrepresented populations. Ironically, this exclusion is at odds with the rapid prototyping/3D printing movement which targeted the inclusionary "Maker movement" which has claimed to increase participation of general audiences in engineering and technology. Further, the Additive manufacturing design process is a fairly experience- and intuition-driven activity. Due to this reason, new engineers entering the AM design profession undergo a longer learning period and must rely on experienced designers for help in effective decision making. A systematic observation and analysis of these activities could help in breaking down the intuitive approach and analyzing the logic behind every key decision. This could mitigate the entry barrier wall for budding designers in AM and the over-dependability on self-learned AM designers. Research questions that Engineering Education research could answer include
    - Who is entering into graduate programs for Additive Manufacturing and design? How can programs be designed for inclusivity?

- If graduate programs target people working in industry, how can programs be inclusive to women, single-parents, and people with infants, families, or elder-care responsibilities?
- What are the perceived barriers to entrance into the AM community of practice?
- What educational opportunities can leverage online learning to be as inclusive as possible to spread information widely?
- How do graduate students affiliated with AM prepare themselves for faculty careers or industry careers? What elements of professional development should be built into graduate degree programs with respect to non-industry focus AM scientists seeking research careers?

Conclusion

The purpose of this paper was to review educational literature related to the discipline of Additive Manufacturing, while situating opportunities for rigorous and foundational engineering education initiatives within AM. With advances in Additive Manufacturing technologies, the engineering education curriculum will have to be re-engineered to address AM implementation challenges. This article surveyed key initiatives proposed for changing the paradigm of AM education and presented necessary amendments in undergraduate and graduate engineering courses. While several programs are formalizing 3D printing and Additive Manufacturing, especially at the graduate level, there are opportunities and challenges developing educational programs that can leverage or serve to contextualize engineering education research. The emergent state of AM education necessitates the inclusion of engineering education research efforts to tackle underlying issues as the field emerges, such as those related to curriculum, teaching and learning; development of expertise; and diversity, equity, and inclusion. Many of these focuses will be applicable to graduate-level engineering education, because of the specialization and development of expertise that AM requires; however, our vision for engineering education research in Additive Manufacturing can be extended to specialized undergraduate programs or courses as well.

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