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EMPLOYING EYE TRACKING, SCREEN CAPTURE AND ARTIFACT ANALYSIS METHODS TO CHARACTERIZE RE-DESIGN FOR ADDITIVE MANUFACTURING BEHAVIORS

A Thesis in

Additive Manufacturing and Design

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ABSTRACT

Additive Manufacturing (AM) has attracted significant interest from industry and academia practitioners all around the globe. The design freedom offered by this technology along with a considerable reduction in lead times are key factors catalyzing its proliferation. Engineering designers are optimistically counting on AM to help them reinvent the product development life-cycle. A key influence to accelerate the adoption of AM is developing a multi-disciplinary workforce to meet the ever-increasing demand-supply gap. Designers of the future will require inter-disciplinary skill sets to adopt, evaluate and progress AM technologies. To help engineers optimally reap the benefits of the design freedom offered, a new design thinking approach coined as “Design for Additive Manufacturing” is recognized by industry and academia practitioners. Engineering designers are often tasked with re-designing a component or assembly for AM, which is traditionally intended for conventional near-net manufacturing processes. Existing research directives in the Design for AM arena focus on design optimization frameworks, worksheets and guidelines which provide a check-list for designers during the execution of the DfAM methodology. However, few research initiatives are invested towards understanding or characterizing the behaviors of designers performing a re-design activity. Such a synthesis would allow researchers to qualitatively understand design behaviors which can be then related to design success from the AM perspective. This thesis provides a systematic literature review of the state of the research in AM engineering education, followed by the first known qualitative characterization of the re-design for AM process employed by engineering designers during a design challenge. The design challenge essentially consists of a single objective optimization problem of re-designing an airplane bearing bracket for AM, particularly for the Laser Powder Bed Fusion (L-PBF) process. The complete re-design process is recorded using eye-tracking and screen capture methods using visual gaze pattern data. Design behaviors exhibited by engineers are characterized qualitatively using constant comparative methods derived from the traditional cognitive and human subject research literature. The designs generated by participants are analyzed using a novel manufacturability matrix, developed by the authors specifically for the L-PBF technology. The designs generated are then compared using a normalization approach, where a manufacturability index is derived to highlight participant performance. Aggregate behaviors from designers are compared and contrasted using content analysis methods to link designer behaviors with success in generating a design to match or exceed the manufacturability requirements for AM. The redesign for AM process is primarily driven by intuition, logical judgments, and application of engineering first principles. Results from this research highlight the differences in behaviors exhibited by novice and expert engineering designers challenged with the same optimization problem. It is observed that participants spend a significant portion of their total activity time on stress analysis and sketching related activities. A major portion of the total time spent by designers is invested in 2D Sketching related activities, which highlights the need for non-parametric software to suit the re-design for AM process. With data acquired from the participant approaches, a re-design for AM workflow is presented to encourage behaviors to correspond with success in manufacturability for the L-PBF process. Implications from this study will serve engineering designers to develop a comprehensive understanding of the approach and methods used during the (Re) Design for AM process. The designer-centric workflow presented in this study can be used as an aid by the engineering education and research community to help educate students, appreciate the re-design for AM workflow.

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Chapter 1

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, in AM, material is *added* instead of subtracted 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 AM is noteworthy caused mainly by quality and value addition which AM proposes in the product development process: shorter lead times, less waste, and competitive products. 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].

Chapter 2 presents a systematic literature review of AM education with a focus towards graduate level curriculum. Observations about the current state of graduate level education is presented with an in-depth analysis of efforts from universities towards addressing this issue. The US also faces a severe shortage of workforce to address the talent gap and recommendations are made towards efforts which have potential to close the demand-supply gap. Design for Additive manufacturing is one of the key skill sets required to accelerate the adoption of AM. Current research provides recommendations on frameworks and checklist for re-designing a part for AM. However, limited research efforts have been directed towards understanding and characterizing the re-design for AM process. Chapter 3 provides results from an empirical study from the design processes of six graduate student engineering designers as they re-design a traditionally designed part for additive manufacturing. Behaviors through the design task are compared between the study participants with a quantitative measure of the manufacturability and quality of each design. Results indicate opportunities for further research and best practices in design for Additive manufacturing and engineering education practitioners across multiple disciplines. There is a significant amount of difference between the approach adopted by novice and expert designers while re-designing a part for Additive manufacturing. The results and similarities between the behaviors of both these groups are presented in Chapter 4. Chapter 5 outlines the conclusions and presents future scope of work possible within the amalgamation of AM and engineering education domains.

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Chapter 2

A SYSTEMATIC REVIEW OF ADDITIVE MANUFACTURING EDUCATION: TOWARDS ENGINEERING EDUCATION RESEARCH IN AM

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Abstract

Additive Manufacturing 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. AM 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.

2.1 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 chapter 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?

2.2 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.

2.3 Chronological Review of AM Education Efforts

The literature on AM 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.

2.4 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.

2.5 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

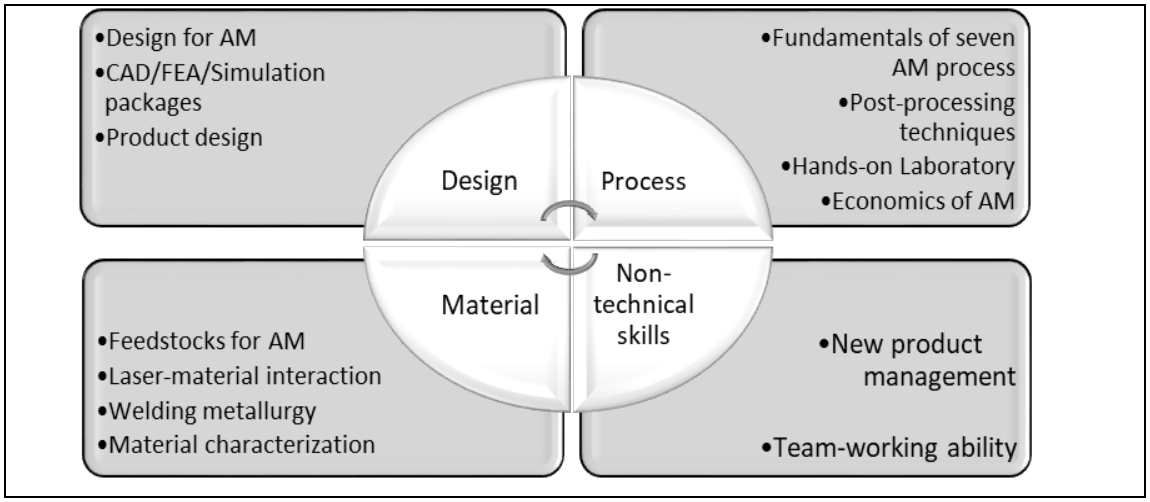

Figure 1 : Synthesis of Desired AM Curriculum Content

AM research, discovery, creation and innovation and offers apprenticeships, co-ops, and educational facilities to promote 3D-printing and Additive manufacturing education [18].

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?

2.6 Conclusion

The purpose of this paper was to review educational literature related to the discipline of AM, while situating opportunities for rigorous and foundational engineering education initiatives within AM. With advances in AM 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 AM, 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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Chapter 3

AN EMPIRICAL STUDY LINKING ADDITIVE MANUFACTURING DESIGN PROCESS TO SUCCESS IN MANUFACTURABILITY

This chapter is published in the proceedings of the Solid Freeform Fabrication conference*: Priyesh Mehta, Catherine Berdanier, Manoj Malviya, Colin Miller and Guha Manogharan (2019). An empirical study linking additive manufacturing designer's behaviors to success in manufacturability*

Abstract

This chapter characterizes engineering designers' abilities to re-design a component for additive manufacturing, employing screen capture methods. Additive Manufacturing has garnered significant interest from a wide range of industries, academia and government stakeholders due to its potential to reform and disrupt traditional manufacturing processes. The technology offers unprecedented design freedom and customization along with its ability to process novel and high strength alloys in promising lead times. To harness the maximum potential of this technology, designers are often tasked with creating new products or re-design existing portfolios of traditionally manufactured parts to achieve lightweight designs with better performance. To date, few studies explore the correspondence between design behaviors and manufacturability of final product within an Additive Manufacturing context. This chapter presents empirical data from the design processes of six graduate student engineering designers as they re-design a traditionally designed part for additive manufacturing. Behaviors through the design task are compared between the study participants with a quantitative measure of the manufacturability and quality of each design. Results indicate opportunities for further research and best practices in design for Additive manufacturing and engineering education practitioners across multiple disciplines.

3.1 Introduction

An explicit focus on Design for Additive Manufacturing (DfAM) is growing to be an attractive avenue for researchers and industry to leverage the potential of Additive Manufacturing (AM), a field that has witnessed significant research and development in the last decade. While most research focuses on process and material properties, relatively few researchers explore the human contribution to the additive processes. Recent DfAM research efforts seek to address this opportunity gap by developing novel frameworks to help accelerate implementation of design guidelines which would create components and assemblies best suited for AM [1-4] . These frameworks provide a skeleton for the iterative ideation and conceptualization process as a checklist to help designers create novel ideas for this technology. While a strict DfAM approach is inherently valuable, few researchers study how designers re-design an existing traditional part or assembly for AM. The current trend in the industry for success in AM is to identify a set of existing parts from product families designed for conventional manufacturing, and re-design it for AM [5].

In such cases, there is a need for design guidelines, frameworks and workflows to help designers systematically approach the re-design process. Existing methods can be useful for application in the conceptualization stages of the re-design process, but designers still need assistance in making re-design decisions when looking to modify an established component[6]. Schmelzle et al provides a holistic framework approach with help of a case study towards re-designing an existing assembly by part consolidation [7]. An effort like the one adopted by Schmelzle directed towards developing a re-design workflow for shape optimization and weight consolidation is required for AM. While most DfAM research efforts aim to create a process/skeleton or framework to investigate the direction in which the re-design should be performed, there is a scarcity of literature studying explicitly how the re-design process occurs, especially with participants having basic or higher knowledge of AM theory and principles.

This paper attempts to quantify and characterize the re-design methodology adopted by graduate engineering students when re-designing a mechanical component for the laser powder bed fusion (L-PBF) process using eye tracking and screen capture methods. The structure of the paper is as follows: We provide a brief review or relevant literature, discuss methodological information for our empirical study including recruitment; participant profile; design prompt; data collection methods; and analysis protocols. The results explore the behavioral patterns of the designers through the re-design process and map them with a metric of quality for the final designs, evaluated using a proposed normalized manufacturability matrix for the L-PBF process. The findings motivate future research directions and implications for practitioners as discussed in the conclusion section.

3.2 Background

Design for Additive Manufacturing (DfAM) is the consolidation of shapes, sizes, geometric meso-structures, and material compositions and microstructures to make optimum use of capabilities of the AM process [8]. Organizations like General Electric and NASA have adopted DfAM approaches to achieve part consolidation and reduce the weight of the overall part without compromising the functionality of the part [9]. The development of knowledge of DfAM principles, rules, processes, tools and methodologies have been identified as one of the key challenges in mass adoption and implementation of AM, motivated by the realization that a designer's lack of knowledge of AM principles prevent designers from optimally reaping the benefits of Additive technologies [10].

Re-designing a traditionally-manufactured component for Additive Manufacturing can be performed using a variety of process and objective oriented frameworks, usually with human intuition and engineering decisions [1], combined with automated processes aided by design software tools. One such tool is topology optimization (TO), a structural optimization tool used to optimize material distribution of structures to improve stiffness or other pre-defined objectives. Since the topology optimization algorithmic process removes material from all areas and locations where it is not required to support the specific loads or satisfy specific boundary conditions, the resulting geometries often contain structures that are not uniform in cross section. These structures sometimes resemble bones or tree branches; hence, the process is also known as bionic or organic optimization [11]. TO is a powerful approach for determination of optimum material distribution under a specified design domain. However, there are several limitations associated with implementation of TO methods for AM; namely - mesh resolution, manufacturing constraints and post-optimization topology handling [12]. Several research studies have tested the efficacy of designers with and without the use of proposed design heuristics and are proved to be effective towards achieving better and improved designs[13-16]. Re-design activities have also been classified into process-driven and designer-driven optimization, showing that a high possibility of the re-designed AM part becoming as much as 30 times more expensive to manufacture than the original design pressing in the need to validate the performance-cost tradeoff [17]. Further, there are frameworks associated with re-design methodology for AM focused on analyzing the end results of the design process, but to date no literature has been published characterizing engineering designers' processes adopted while re-designing for AM frameworks. This process is primarily driven by intuition and engineering judgements and hence it is worthwhile to investigate the cognitive process, spatial attention division and behavioral activity of designers involved in a re-design for AM task. Therefore, the research questions this study seeks to answer are as follows:

1) What design behaviors do engineering designers employ when conducting a (re)Design for Additive Manufacturing task?

2) How do designers' behavioral patterns correspond with manufacturability metrics of the final designs?

3.3 Methods

The research design for this study employed human subjects' research methods consistent with empirical research studies in design cognition and engineering education bodies of literature. After IRB approval, engineering graduate student participants were recruited to participate in a design challenge. The following section outlines methodological considerations involved in recruitment, data collection, and data analysis.

Recruitment and Participants: The participants for this research were recruited from a graduate level laboratory course at a large public university where the course objective was to provide hands-on experience with metal AM technologies. After obtaining IRB approval for the project, students were recruited to participate in a design challenge which involved re-designing a component for AM. Six master's-level students chose to participate in the study. All participants had been enrolled in a specialized master's curriculum in Additive Manufacturing and Design for at least one semester prior to data collection and hold at least a bachelor's degree in an engineering discipline related to AM. Of the six participants, one was a woman. The number of woman participants, though low, are representative of graduate engineering populations in the United States [18]. The design challenge and data collection activities were conducted in the research team's laboratory. Each participant conducted the design challenge individually on the laboratory machines, which are equipped with SolidWorks [19], Autodesk Fusion 360 [20] as well as eye tracking and screen capture data collection capabilities. The participants had been previously exposed to the workflow of laser powder bed fusion as part of the final class project. Therefore, it is assumed that the participants were aware of the preliminary opportunistic and restrictive design considerations along with post-processing workflow associated with the L-PBF technology.

Design prompt: The part used for the re-design challenge was an airplane bearing bracket component from Alcoa Corporation. This design was used as part of an open crowdsourcing competition by GrabCAD [21]. The goal is to minimize the mass and optimize for weight and strength while fitting within the target envelope and meeting the technical requirements. The design prompt presented to the participants included re-design objectives, design requirements, loading conditions and material properties for simulating performance. The prompt also indicated that the part had to be re-designed for the laser powder bed fusion technology as shown in Appendix A. The intent behind selecting an open source design was to benchmark against a well-studied case for AM re-design which allowed the researchers to focus more on the re-design activity and decision-making process rather than investing time in creating a new design with loading conditions. There are other advantages of using open source competition such as cost, sustainability and quality as highlighted by Morgan et al [22]. The participants were provided with the original CAD model and initial stress analysis data in Fusion 360[20] to help in the initial re-design process.

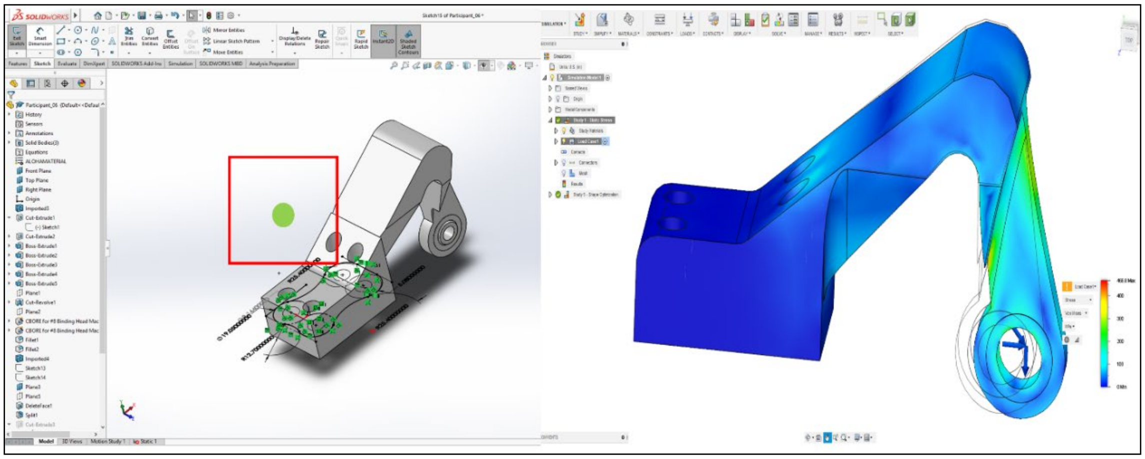

Figure 2 : With the use of gaze tracking, the participants' attention patterns were identified

Data capture: The goal was to capture the visual behavioral activities using eye tracking and screen recording equipment. The FOVIO FX3 screen-based eye tracker from EyeTracking Inc was used to observe visual attention of participant using the gaze point (red colored square) in case multiple windows are used on the same screen as shown in Figure 2. For the 90-minute re-design activity, participants were also instructed to indicate the build orientation of the part and were advised to avoid using lattice structures for light weighting. The use of lattice structures would have diverted the attention of participants from using the shape complexity design freedom offered by AM to hierarchal complexity which was not desired [23].

Analysis of Human Design Behaviors: Analysis of the screen capture data occurred through qualitative data analysis methods for real-time data, as developed and validated by the research team in past literature for other observational data in engineering education research contexts [24-25]. The corpus of data to be analyzed comprises six sets of logged CAD and visual activities representing the design processes of the six engineering student participants. Consistent with qualitative methodological traditions in engineering education literature and design thinking literature, behaviors can be sorted into representative functions such that each behavior could fit into a more generalizable theme, grouped with similar behaviors using well-established methods for the constant comparative method proposed originally by Glaser and Strauss [26] and well-accepted across all disciplines who employ any qualitative data analysis [27]. The first step in qualitative categorization is to develop a "codebook" through constant comparative methods to define a comprehensive set of behaviors, which are also known as codes. Open and axial coding methods allow researchers to group codes into overarching themes. In our case, we used a combination of *a priori* and emergent coding methods to develop themes, employing standard language from the basic functional use of SolidWorks features combined with researcher descriptions of the participants' attention patterns.

Table 1 depicts the codebook for this data to describe the screen recorded and eye tracking behavioral data captured from the six participants. The different kinds of activities and spatial attention focus were grouped into three major categories of *verification*, *composition*, and *modification*. The *verification* category included the span of time which was spent by the participant on stress analysis, reading the design prompt and visual inspection of dimensions and geometry for

AM feasibility. Activities like considering overhang angles, support structures and build orientation were included in the inspection category. The stress analysis category included visual attention of participants when they are observing initial FEA results provided in Autodesk Fusion 360 in addition to carrying out iterative FEA analysis on the geometry re-designed by them. The *composition* group includes the time spent by participants using extrude and sketch features in SolidWorks primarily used for creating a new geometric feature. Use of features like smoothing, fillet and revolving were categorized in the revising group under *modification* category. Making changes to the existing sketch or new sketch created by the participant was also included in the revising group. Editing of existing and newly created sketches and changing/scaling dimensions of geometries was included in the editing sub-category. Activities which include eliminating and removing material using cut/extrude features are included in the remove material group.

Table 1 - Codebook for qualitative data analysis methods

OVERARCHING THEME	BEHAVIORAL ACTIVITY "CODE"	DESCRIPTION	CODE NUMBER
Verification	Stress Analysis	Observing FEA results and performing stress analysis on created component	1
	Requirement/Design prompt	Focusing on problem and objectives	2
	Inspection	Inspecting dimensions and considering AM restrictions	3
Composition	Add material	Adding new features	4
	Sketching	Sketching	5
Modification	Revising	Smoothing existing features and using Fillet function	6
	Editing	Editing sketch, changing dimensions	7
	Remove material	Removing existing features	8

For the purposes of developing time stamp and frequency data of each activity, we then assigned each code a numerical value for ease of data processing in MATLAB and MS Excel. The numerical values have no significance on importance or order (e.g., category 1 is not superior or inferior to category 3), but are useful for computational bookkeeping purposes, a method applied in other studies [28-30]. The behavioral data, represented by numerical values, was then be analyzed as a function of the percentage of the total time spent which is further discussed in the results section.

Quantifying Design Manufacturability. After each participant completed the design challenge, the study aimed to quantify the design quality of each of the re-designed CAD model based on the primary criteria of weight, build time estimate, total volume, support volume and strength expressed via factor of safety. The support structures are generated using the standard SLM parameter set with a support critical angle of 35° on Autodesk Netfabb [31]. The parts were repaired using the extended repair script from Netfabb and then loaded into the EOS M290 machine workspace. The build strategy of EOS Print Standard Parameters set 30 microns for Stainless Steel 316 available in Netfabb was selected. The parts were raised by 1.5mm above the build platform to account for the wire EDM process. Once the build was ready with the support structures, the slice data was exported to ATLAS 3D [32] to simulate the laser powder bed fusion build process to predict thermal distortion and possibility of re-coater interference. The EOS M290 SS316 L parameters were selected for simulation on ATLAS 3D. The entire process workflow was repeated for all six participants as depicted in Figure 3. The manufacturability matrix table is generated using part details, build details and simulation metrics of all six participants. This matrix is specific to the laser-powder bed fusion process only

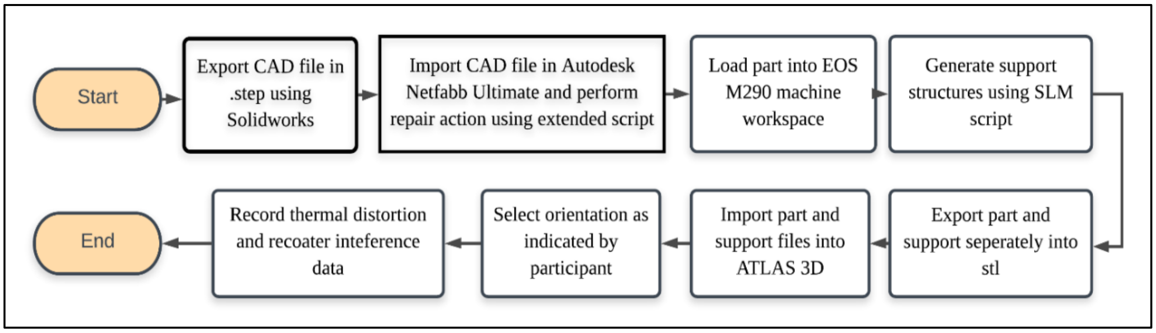

Figure 3 : Data analysis workflow for participant-generated CAD file

3.4 Limitations

As with any study, there are limitations due to study constraints. In particular, we acknowledge that this is a very small sample size; however, even six participants yielded several hours of data to analyze. Preliminary analysis of this data is also required in order to accurately pursue and analyze larger data sets with more participants. Another limitation is the population: While these are experienced designers who have DfAM formal education, they may not be experts in these areas. The re-design activity required a certain level of proficiency in CAD, which is not the same for all participants and may have affected performance in the re-design challenge. The categories in which the behavioral activities are divided is not based on any proven model and hence further validation is required. Lastly, the analysis and coding for this paper was accomplished by a single researcher, such that in more robust studies, interrater reliability will need to be calculated to as one way of establishing quality in qualitative data.

3.5 Results

The findings for this study are discussed first by analyzing the quality of the re-designed AM part using the criteria for manufacturability as listed in the Methods section. The manufacturability index will then be used to compare the designs across participants. Armed with this information, the designers' individual behaviors will be analyzed with respect to the various performance of their designs in terms of manufacturability.

Manufacturability Matrix for Participants' Final Designs. The criteria for manufacturability (Weight, build time, volume, support volume, recoater interference, thermal distortion, and strength factor) were compared for all participants and compared with the original traditionally manufactured part that the participants were challenged to re-design. The results are shown in Table 2.

Table 2 : Manufacturability matrix from all six participants compared with original traditionally-manufactured part design

Manufacturability matrix	**Participant Number**						
Criterion	**1**	**2**	**3**	**4**	**5**	**6**	**Original**
Weight (grams)	309.23	289.05	529.46	785.26	526.53	662.4	868.38
Build time estimate (hh:min)	15:56	15:44	22:17	28:51	21:28	25:27	30:42
Volume (cm^3)	39.47	36.9	68.82	101.45	66.1	84.63	110.86
Support Volume (cm^3)	2.63	2.71	4.04	3.68	2.2	3.43	3.47
Recoater interference	No	No	No	Yes	No	No	No
Thermal distortion (± mm)	0.58	0.75	0.92	1.17	0.77	0.76	0.81
Strength (Factor of safety)	1.208	1.212	1.864	2.483	2	2.705	2.14

The participants clearly varied in their approaches to redesigning the part, with wide variances in resulting weight compared to the original design (ranging from approximately 309 to 785 grams). All redesigns from the six participants resulted in a decreased part volume, and most resulted in a decreased support volume. The other criteria can be compared by inspection.

Comparison of manufacturability index for participants. Since there is no specific index or ranking system established in academic literature to quantify the manufacturability of parts for AM, we adopted a normalization approach based on Marler et al. [12], where metrics of from all other participants are compared with the best performing participant in each category and the derived value is therefore normalized. The normalized stacked bar chart is shown in Figure 4. The longer the bar of a participant in a certain category, the better the performance of the design in that manufacturability criteria.

As shown in Figure 3, the behavioral activities of each participant are ranked in comparison with the best in that category ranked as 1.00. For example, Participant 2 has the lowest build time estimate compared to all other participants and a lower build time results in a more favorable design for AM. The design generated by Participant 2 has the lowest build time estimate, least overall and support volume, highest strength to weight ratio and lowest weight reduction; therefore, distinctly performing best in this design challenge. The build plan for Participant 02 is provided in Appendix B. In contrast, the design created by Participant 4 has the shortest bar length for all performance categories (except support volume) which renders it to be the least favorable design for manufacturability. The build plan for Participant 04 is provided in Appendix C.

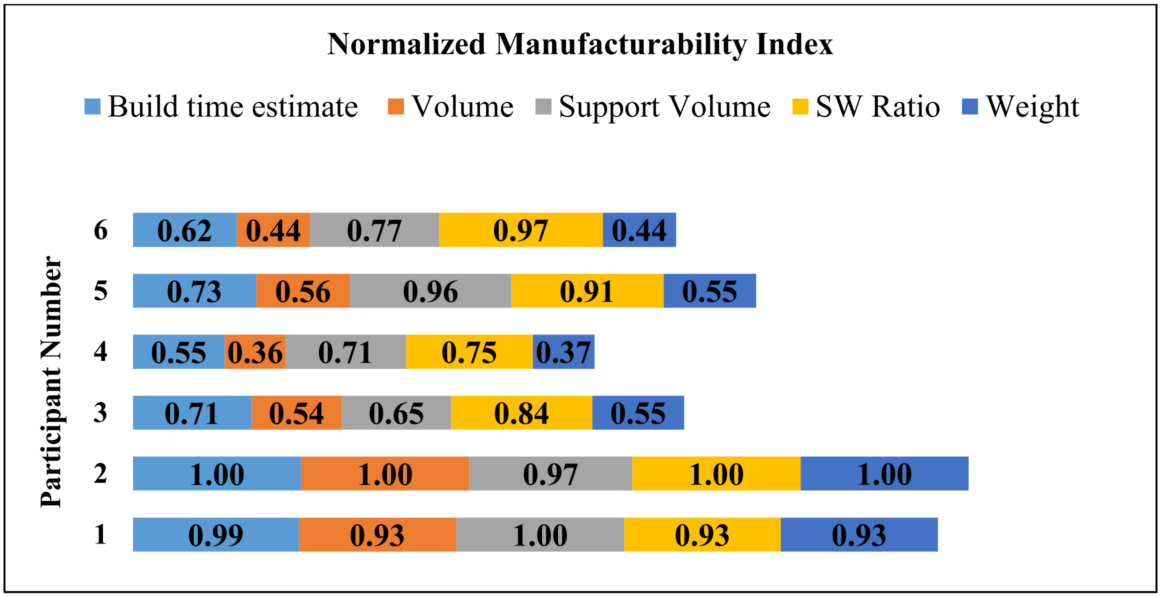

Figure 4 : Normalized manufacturability analysis comparing participant designs

Aggregate Analysis of Designer Behaviors during Design Challenge. The quality of a particular build is interesting with respect to the proportion of total time each designer spent on a given code (i.e., a given behavior or category as per our qualitative codebook). To visualize the aggregate view of the proportion of total time spent by each designer on a particular activity, we employed content analysis methods to quantify the qualitative data collected from participants in this study. As an example, if a designer's process involved spending 10 minutes on stress analysis out of a total of 100 minutes, the behavior would be plotted at the 0.1 mark for that participant, thereby normalizing the plots of all six designers' design processes. Figure 5 shows a line plot of the codes from each of the participants, showing that stress analysis and sketching are the two major categories where participants spend their time. The interpretation of the results obtained from this line plot can be employed to discuss the behaviors involved in re-design; the effect of behaviors on re-design quality; and recommendations for a process workflow that designers might find useful during the Redesign for AM process.

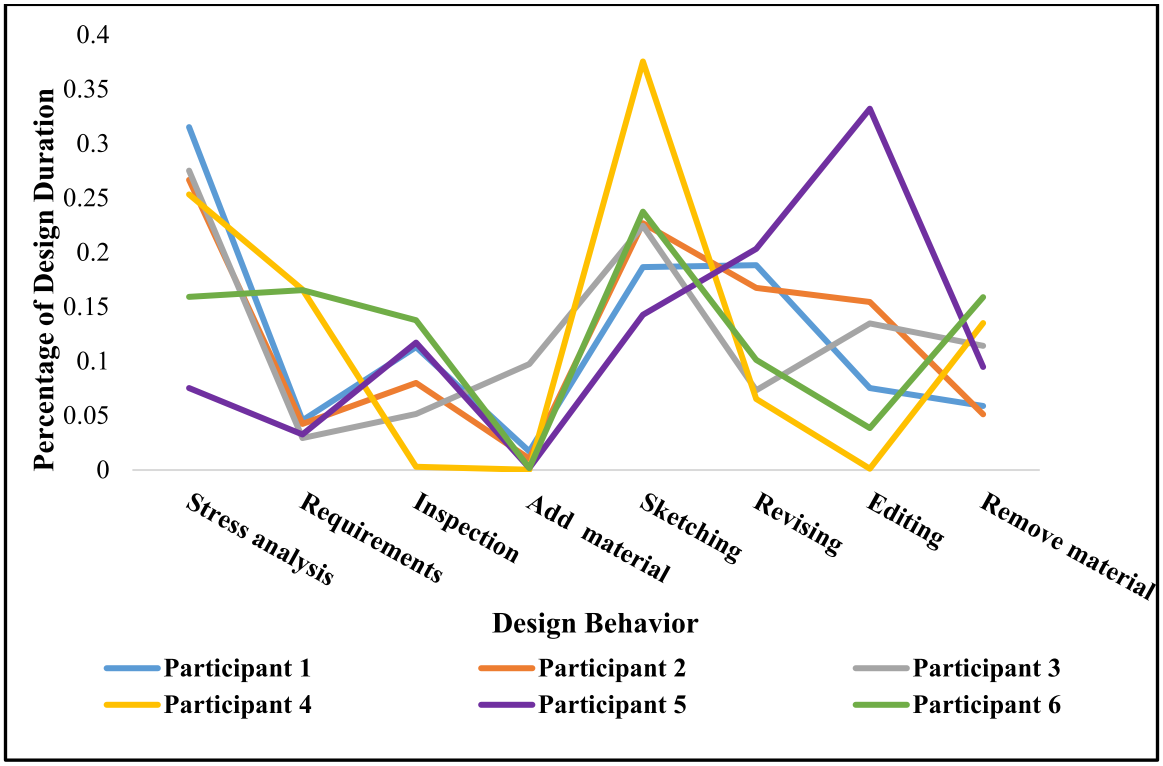

Figure 5: Percentage of total design challenge time spent on each activity

The behaviors represented in Figure 5 emphasize how different the time allocations were between the participants. Anecdotally, one may posit that a re-design challenge activity would be dominated by activities that are directly related to removing the material from the component. However, from the results in Figure 5, participants spent a major portion of their time in stress analysis and sketching related activities. These sketching activities primarily include creating a 2D sketch for removal of material, which is one of the major limitations of parametric software such as SolidWorks. Each participant (except for Participant 5) spends at least 15% of their total time in sketching, whereas the least amount of time is spent on adding new material which is intuitive.

These results also show potential trends to determine which activities most impact final design manufacturability, and therefore, effectiveness. For example, Figure 4 also shows that the design from Participant 2 was ranked first in weight, build time, volume and strength-to-weight ratio, making the best re-design amongst the group of participants. The re-designed model is 66.71% lighter and takes 48% less build time compared to the original model. Observing the behavioral activity of Participant 2 from Figure 6, 34% of the total time is spent on stress analysis related activities. A similar trend is also observed with Participant 1, where more than 30% of the total time is spent on stress analysis related functions, which resulted in an effective design ranked first in support volume and second in all other manufacturing parameters. On the other hand, Participant 4, who had the least effective design, spent a large portion of time in sketching-related activities, and did not spend much time editing their sketch. While the results from this study point toward the trend that spending more time on stress analysis may result in a more effective design rather than other activities, we cannot claim generalizability, statistical significance, or effect size at this point. Future work with a larger sample size of participants will yield statistical conclusions, and may point to indications that combinations of behaviors, or a certain pattern of occurrences within the design task that may matter to manufacturability.

3.6 Discussion

To the best of our knowledge, this is one of the first studies in the design (or re-design) for AM literature that discusses the role of designer behavior on the manufacturability and efficacy of the final additive design. As shown in our results, the participants who ranked the highest in manufacturability exhibited some of the same characteristics, namely, significant attention on stress analyses rather than other behaviors. In contrast, the participants who generated low performing designs spent a great deal more time on sketching rather than stress analysis.

Although this is a small sample size, there are implications from this research that will inform future research directions and practice in the DfAM body of knowledge. First, AM education should focus on developing designers' habits of mind to focus first on the activities that result in a higher performance. Based on our preliminary results, that would mean reminding students to spend more time on stress analysis than sketching or other more intuitive design tasks.

Based on the findings from this study, we suggest a designer-centric workflow to teach effective re-design processes for AM, focusing on designer behaviors. A relatively simple approach of re-designing a part, specifically for the laser powder bed fusion process is proposed as shown in Figure 6 based on this empirical study. This workflow is valid for re-designing a single part with fewer number of loading and boundary conditions where designers engineering intuition can be used for deciding the optimal material distribution.

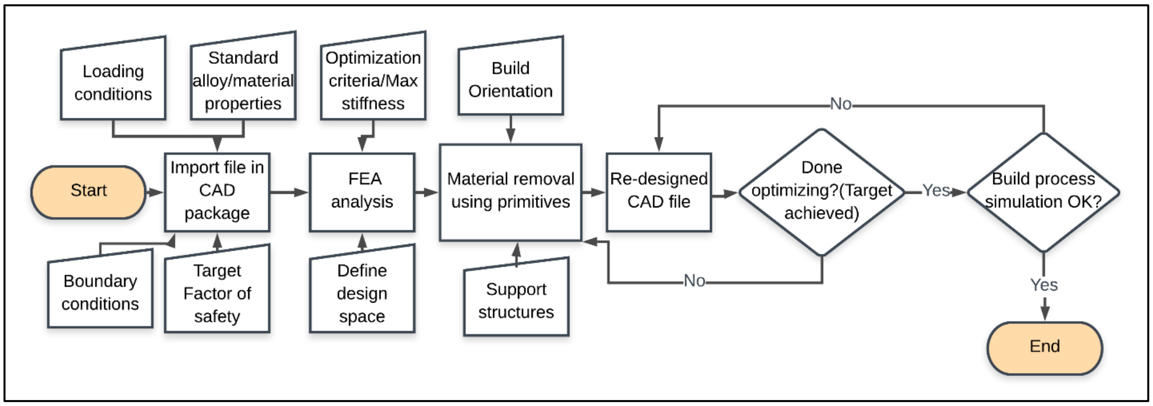

Figure 6 : Proposed workflow to encourage behaviors that correspond with manufacturability in Re-design for Additive Manufacturing processes

In future work, we plan to validate the effectiveness of this process flow-chart in by extending our study to a larger number of participants in order to understand the statistical effects of spending more time on one activity than another. The application of this process workflow will require preliminary understanding of opportunistic and restrictive design considerations of the laser powder bed fusion process. The re-design process chart can also be used by Additive manufacturing design educators for an introductory exposure to the re-design process. Other future work includes the advanced analysis of time-resolved design data from participants to elicit valuable heuristics that can optimize designer behaviors and education in industry and academic settings; evaluate the effect of behaviors, combinations of behaviors, and occurrence patterns with manufacturability; and conducting comparison studies between expert AM designers with novices. In this way we intend to systematize and characterize the art of DfAM to translate more effectively across sectors interested in Addive Manufacturing.

3.7 Conclusion

This empirical study investigated the design processes of six graduate-level engineering designers specializing in additive manufacturing as they were challenged to re-design a traditionally manufactured part to be optimal for Additive Manufacturing. The participants' decisions were captured using screen capture and eye tracking methods, as well as the action log of design software. The behaviors of the designers were qualitatively coded and compared with the final design efficacy, measured in terms of manufacturability based on several key parameters. Our findings indicate that the participants who designed the most effective designs spend more time performing stress analyses on their designs. Implications from this study, if upheld by future work with a larger sample size, indicate that DfAM education might benefit by guiding designers to focus on activities that have a more substantial impact on design quality. To our knowledge, this is one of the first studies that links AM designers' behaviors to manufacturability in the context of design and re-design for additive manufacturing.

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Chapter 4

DESIGN FOR ADDITIVE MANUFACTURING: A COMPARISON OF NOVICE AND EXPERT PRACTITIONER DESIGN BEHAVIORS

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Abstract

Design for Additive Manufacturing is the key to unlock the potential of design freedom offered by this freeform manufacturing technique. In this paper, we report findings on an empirical study of nine designers challenged to re-design a part for the Additive Manufacturing process. Categorically, we extend our previous research that studied graduate student designers to also include a small sample of expert designers with professional experience in AM. In this research, participants are provided with a design challenge in which they attempt to re-design a traditionally manufactured part for AM, considering a variety of constraints. The participants' design activities were recorded using screen capture and eye tracking methods. The data was analyzed using behavioral analysis techniques based on constant comparative methods for qualitative research. Behaviors analyzed from the design challenge are identified into categories and design success is measured using a novel manufacturability index developed by the authors. These results also show that there are significant difference in quality of designs generated by experts and novices, and the frequency of design behaviors give insight to the reasons for the quality differential. Key findings with respect to expert versus novice behavior and design success are discussed with opportunities for future work in design engineering education research.

4.1 Introduction

Additive Manufacturing (AM) is the process of selectively joining layers of material using different sources of energy such as laser, electron beam, heat or UV light. The layer-by-layer nature of building parts is what makes AM unique when compared to subtractive and formative technologies like CNC and casting. The adoption of AM into mainstream has been on the rise on account of its recognition to offer significant advantages like design freedom and faster time to market. Due to the “build up” nature of AM, new paradigms of design, process and material innovations are emerging. To harness and take advantage of these new capabilities, efforts have been directed to focus research and development on creation of a new design paradigm. The term “Design for Additive Manufacturing (DfAM)” promotes the adoption and education of this abstract concept [1]. There have been numerous efforts from the industry, academia and government to proliferate adoption of DfAM to help users with guidelines and frameworks to design specifically for this technology [2].

With recent advances in the design exploration process and increased interactions with computer aided algorithms, the product design process has been significantly reinvented. AM has catalyzed the re-emergence of generating designs through alternative methods [3][4]. Such alternate methods not only provide the user with data-driven assistance in decision making, but also help them generate a wider range of possibilities for design selection. Even with the availability of different data driven, computer aided design generation methods, majority of organizations still prefer plain vanilla design development methods [5]. Human involvement engineering design still remains prevalent, because modern generative design tools are fairly new and have to address many issues before they become mainstream[6][7].

A majority of DfAM research efforts directed towards helping designers generate designs to make optimum use of AM comprises skeletons, frameworks and worksheets [8-11]. These approaches are useful typically when a new product or component is being designed from scratch. Large organizations like General Electric, Honeywell, Ford have already adopted AM as part of their prototyping and manufacturing process[12][13]; such large companies have existing design and part repositories with over millions of existing generated designs. In such situations, it is nearly impossible for them to create an altogether new set of designs to suit AM. Hence, it is viable for companies to explore re-design for AM, where an existing part is modified considering the opportunistic and restrictive design principles of AM [14]. Therefore, the current tendency in the industry is to identify candidates for AM from the existing design warehouse and re-design it for AM [15].

To characterize the re-design for AM process, it is imperative to understand behaviors adopted by designers along with the types of approaches adopted to achieve success. In this paper, we investigate the design behaviors, attributes and methods adopted my engineering designers to re-design a part for AM. We conduct human subject experiments with novice and expert designers solving a design challenge with the same optimization target. This paper empirically examines the re-design process adopted by designers at a variety of expertise levels to characterize the differences in methods, process and behaviors.

The structure of the chapter is as follows: We provide a brief overview of literature relevant to engineering design process characterization, discuss methodological information for our experiment including recruitment; basis of analysis method selection; participant profile; design prompt; selection of data collection methods and analysis protocols. Behaviors are then linked to design efficacy of the resulting re-designed part, where design efficacy is measured using a novel manufacturability matrix developed specifically for the laser powder bed fusion process. Results from this empirical research provides new insights to engineering education researchers and practitioners about the kinds of design skills to instill and foster in student designers, and for practitioners who are learning to re-design for AM. The path to evolve from a novice designer to an expert engineering designer will be highlighted with which a success template can be created for future design engineers. The qualitative design behaviors when linked to design success motivate future directions for research and implications for engineering designers and practitioners as discussed in the results and conclusion section.

4.2 Review of related literature

Quantitative and qualitative comparison of performance between novice and experts is well recorded in literature [16][17] to categorize behaviors or create heuristics.With respect to engineering design, there have been a few studies conducted to establish contrasts or similarities between novice and experts [18-21]. The terminology adopted for novice and expert individuals differ with each study. Proficiency levels can be assessed my measures such as academic qualifications (graduate versus undergraduate), experience or years of performing a particular task, or simply consensus among peers [16]. Wolf et al. [22] investigated the effectiveness and efficiency of interactive trade exploration strategies between novice and expert users. One of the papers from Adams et al. [23] aimed to characterize the engineering student design process by understanding the iterative nature of behaviors comparing freshmen and senior engineering students. Atman et al. [24] reported results from an engineering design study comparing senior and freshman engineering students using verbal protocols. Another study from Atman et al. [21] elucidates results from an engineering design activity comparing results between experts and student engineers. One of the key results from this study is that problem scoping and information gathering are major areas of differences between the two groups.

Few studies have been directed towards establishing a relationship between experts and novice designers in the domain of Additive Manufacturing. A recent study by Yang et al. [25] conducted an experimental study to verify whether AM knowledge affects the synthesis of working principles to result in a successful design. Recent experimental studies have also revealed that designers who are provided AM training and knowledge do generate more quantity and quality of design solutions as compared to control groups. A recent work published by Prabhu et al. [26] explored the importance of timing on effectiveness of design for AM education utilizing results from problem- and project-based learning experiments. Significant interest has been visible in research efforts to address the Design for Additive manufacturing opportunity as it affects education, workforce and talent opportunity [27-30].

The re-design for AM process involves a significant amount of decision making and is primarily driven by application of engineering first principles and intuition. Past literature suggests that the methods in which experts and novices approach a given design optimization problem is different [19] [21][25], and these cognitive processes, behavioral activities, and judgements executed during the design process lead to the success or failure of the solution generated. A follow-up study investigated the design behaviors exhibited by novice engineering designers when conducting the same re-design activity [31]. A qualitative evaluation of the process adopted by both novice and expert designers can provide insights into the decision making process. To add to the findings from this study, the research questions this empirical study seeks to address are as follows:

1) What typical differences in design behaviors do novice and expert designers exhibit when attempting to solve a (re)Design for Additive Manufacturing challenge?
2) Which types of approach to the design optimization problem yield better success when measured with manufacturability metrics?

4.3 Methods

Once achieving IRB approval to conduct human subjects' research, expert engineering designers were recruited to participate in a design challenge. The subsequent section highlights methodological considerations with justification of choice involved in recruitment, data collection and data analysis.

Recruitment and Participants: The identification and recruitment of experts in our study was done using the relative expertise approach [16]. This approach involves studying a group of individuals expected or presumed to be more proficient in a task (relative experts) related to a group presumed to be less knowledgeable (relative novices). In the relative expertise approach, measures of proficiency such as academic qualification, number of work experience performing the task and peer consensus are used to identify and differentiate experts from novices [21]. With a mixed approach of drawing on a social definition of expertise [19] and the fact that the recruitment was done towards the end of a graduate summer course on hands-on laboratory metal AM technologies, we recruited three expert practitioners (n=3). It has been observed by researchers that the demand-supply gap in workforce with AM skills is prevalent [29]. The expert practitioners who chose to be part of a design challenge were full time working professionals. All participants had been enrolled in a specialized master's curriculum in Additive Manufacturing and Design for at least one semester prior to data collection and hold at least a bachelor's degree in an engineering discipline related to AM. Based on analysis of their responses to a post-design challenge survey on Qualtrics, it was indicated that all of them had taken a formal course in Design for AM. The expert participant's range of work experience varied from 3.5 – 8 years in the industry.

The data for novice designer participants (N=6) were used from previous research with an identical recruitment, data collection and analysis procedure. The novice designers were graduate level students enrolled full time in a master's curriculum in Mechanical Engineering, Industrial

Engineering or Additive Manufacturing and Design. These students were exposed to the workflow of laser powder bed fusion as part of the final class project. Therefore, it is assumed that novice participant pool was aware of the preliminary opportunistic and restrictive design considerations along with post-processing workflow associated with the L-PBF technology. Therefore, the total number of participants for this study is (N=9) with a mix of novice and expert practitioners. Of the total of nine participants, two were woman. The number of low woman participation represents graduate engineering populations in the United States of America [32]. All participants were presented with a design challenge which involved re-designing a part for Additive manufacturing. The design challenge and data collection activities were conducted in the research team's laboratory. Each participant was given instructions to conduct the design challenge individually on laboratory machines which are equipped with SolidWorks [33], Autodesk Fusion 360 [34] and screen capture and eye tracking data collection capabilities.

Design Prompt: The component selected to be re-designed for the design challenge was an airplane bearing bracket from ALCOA Corporation. This challenge was originally developed as part of an open crowdsource competition by GrabCAD to spur optimization of old design geometry for weight and strength. The bearing bracket is a common component on control surfaces of various aircraft parts and provided a great avenue to apply AM principles [35]. The intent behind selecting an open source design was to make use of a well-studied case for AM re-design instead of creating a relatively new component with loading conditions. The primary design optimization objective was to redesign the bracket for AM which could provide significant weight savings, ultimately resulting in reduced fuel consumption. Participants were instructed to minimize mass and optimize for weight and strength while satisfying loading constraints and build target envelope. The efficacy of the design submission was to be evaluated using Finite Element Analysis verification, strength to weight ratio and manufacturability. A digital copy of the design prompt can be found in Appendix A. It was highlighted that the bracket was intended to be manufactured using the L-PBF process. The material properties and loading conditions were provided and it was explicitly instructed to avoid use of lattice structures to light weight the design. The use of lattice structures would have diverted the attention of participants from using the shape complexity design freedom offered by AM to hierarchical complexity [8][36] which was not desired. To aid in the exploration of design optimization during the early stage, the participants were provided FEA results in Fusion 360 along with the original CAD model in SolidWorks.

Data Collection Methods : The goal of data collection was to obtain information on the amount of time spent by each designer on an activity or behavior. A FOVIO FX3 screen-based eye tracker (Eyetracking Inc.) was used to study and observe visual attention of participants using gaze point data. The gaze tracking point is also used to identify attention area in case the participant used multiple tabs on a single screen as shown in Figure 7 (where the gaze tracking point is indicated in the red box). To capture visual activities performed, we used screen video recording, a feature included the eye tracking software. Video data affords access to content surrounding phenomena of interest exhibited by t e participants. Using screen captured video as an exploratory analysis are well-documented methods in human science and cognitive research to qualitatively analyze participant behavior [37][38].

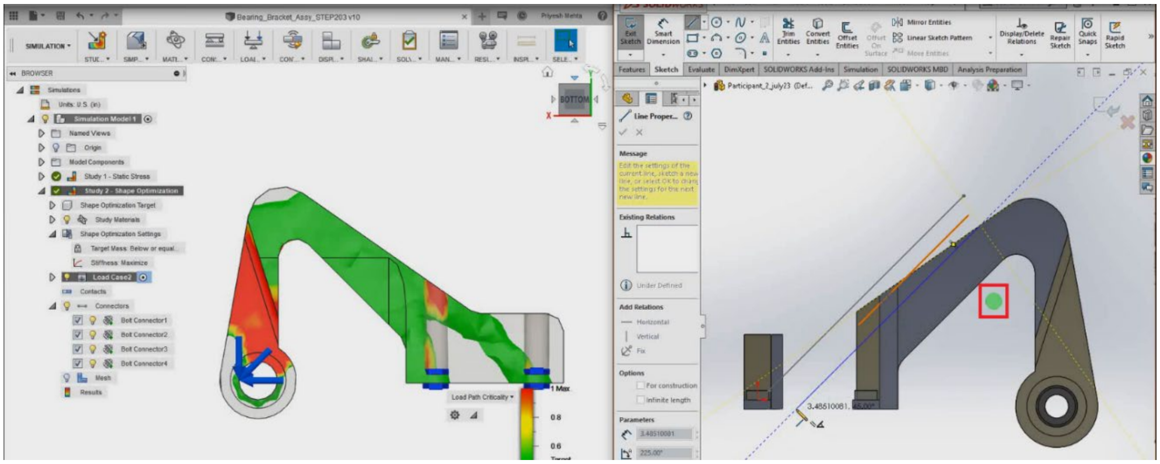


Figure 7 : Red highlighted box showing participant’s visual attention

Qualitative Analysis Methods: Qualitative data is usually non-statistical and is typically unstructured or mainly semi-structured in nature. This type of data is not necessarily measured using firm numbers which are used to develop statistical charts or graphs. Contrarily, the data is categorized based on properties, labels, attributes and other identifiers [39]. According to McMillan and Schumacher (1993, p. 479) qualitative research is defined as, "primarily an inductive process of organizing data into categories and identifying patterns (relationships) among categories" [39]. Since we are attempting to develop theorizations, interpretations and initial understandings of the redesign for AM process, we selected to pursue qualitative analysis which is investigative, flexible, open-ended and more importantly, can be used to ask the question "why" [40]. Qualitative research is a broad term for investigative methodologies described as ethnographic, naturalistic, anthropological, field, or participant observer research. In our case we will focus on participant observer research and use the constant comparative method to categorize and compare recorded data for analysis. The constant comparative method is a procedure to qualitative data analysis in which each finding and interpretation that emerges from the data is compared with existing codes and categories [41].

The video recordings for all nine participants were analyzed to identify common themes throughout the process. In our best knowledge, there has been no research on categorizing behaviors in groups for the re-design for Additive manufacturing process. Hence, with the backdrop of knowledge developed and validated by the research team in previous literature for observational data, we analyzed the screen capture video data using visual analysis methods [42][43]. For our study, we used a combination of *a priori* and emergent coding method to develop themes, using standard design process adopted by engineers. We used the codebook developed in previous research to categorize behaviors into representative functions in a way that each behavior could fit into a more generalizable theme [31].

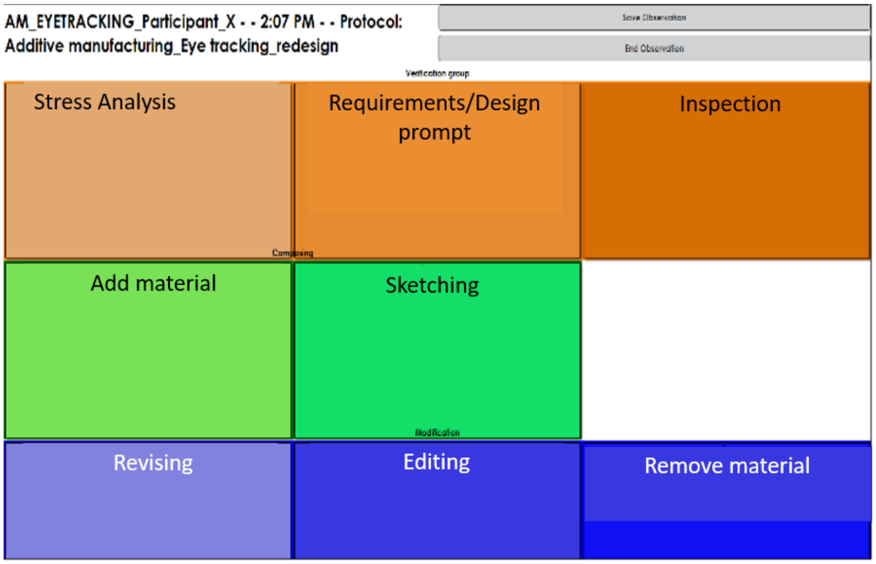
Table 3 shows the codebook for this data to describe screen recorded and eye tracking behavioral data captured from all nine participants. The design challenge coding scheme was developed to reflect models of a conventional engineering design process.

Different types of designer activities and spatial attention focus were grouped into three major categories of *verification*, *composition*, and *modification*. The *verification or problem scoping* category included the amount of time which was spent by the participant on understanding the design challenge, stress analysis, reading the design prompt. The inspection of dimensions and overhangs to account for AM process restrictions were included in the inspection sub-category. Design generation is an iterative process and hence using FEA is important. The stress analysis sub category included time spent by designers in observing and applying loading conditions on both original and self-re-designed versions. The *composition* group consisted of the time spent by participants to create new geometric features and using 2D sketching. The application of features like smoothing, fillet and revolving were considered under the revising group in *modification* category. Making changes to the existing sketch or creating a new sketch was also included in the revising category. The editing of existing and newly created sketches and changing/scaling dimensions of geometries was included in the editing sub-category. Using the cut/extrude features to eliminate and remove material was included in the remove material group. To develop time stamp and frequency data of each activity, we allocated each code a numerical value for easier processing of data in MATLAB and MS Excel. These numerical values have no implication on importance or order (e.g. category 2 is not superior or inferior to category 4). The codes are useful for computational bookkeeping purposes and are in line with other qualitative data analysis studies [44][45][23].

Table 3 : Codebook for qualitative data analysis methods

OVERARCHING THEME	BEHAVIORAL ACTIVITY "CODE"	DESCRIPTION	CODE NUMBER
Verification	Stress Analysis	Observing FEA results and performing stress analysis on created component	1
	Requirement/Design prompt	Focusing on problem and objectives	2
	Inspection	Inspecting dimensions and considering AM restrictions	3
Composition	Add material	Adding new features	4
	Sketching	Sketching	5
Modification	Revising	Smoothing existing features and using Fillet function	6
	Editing	Editing sketch, changing dimensions	7
	Remove material	Removing existing features	8

The data acquired from behavioral analysis are then used to quantify the amount of time spent by each participant on a particular activity defined in the codebook as a function of the percentage of total time.To facilitate the data collection process, we decided to use the GORP Tool to transfer the codebook into an interactive user interface. Built by the researchers at University of California at Davis, the GORP (Generalized Observation and Reflection Platform) is a web-based system for carrying out classroom observations using user defined protocols for analysis of data captured during observation studies (Figure 8). The platform can be used on a mobile touch-screen device and therefore is convenient for capturing observational data. As the coder watched the screen and gaze-capture videos, he manually captured the observations in real-time. The GORP tool then outputs a .csv spreadsheet which captures the coded behaviors as a function of time points. While small differences between may exist if multiple coders were to observe the same data set, this study did not calculate intercoder reliability measurements.



AM_EYETRACKING_Participant_X - - 2:07 PM - - Protocol:
Additive manufacturing_Eye tracking_redesign

Figure 8 : GORP Tool screenshot

Measuring Design Efficacy through a Manufacturability Matrix: After each participant completed the design challenge, we sought to quantify the design quality of each of the designs based on the primary criteria of weight, build time estimate, support volume, total volume and strength indicated with Factor of Safety. The laser powder bed fusion process is one of the most widely used AM technology. The general process workflow for this technology includes build programming activities such as file repairing, build process simulation, support generation and orientation selection.

To reproduce the printing process used in industries to manufacture parts from the L-PBF process, we evaluated each CAD file generated to quantify design quality to derive manufacturability metrics described above. To obtain design evaluation data, all re-designed CAD

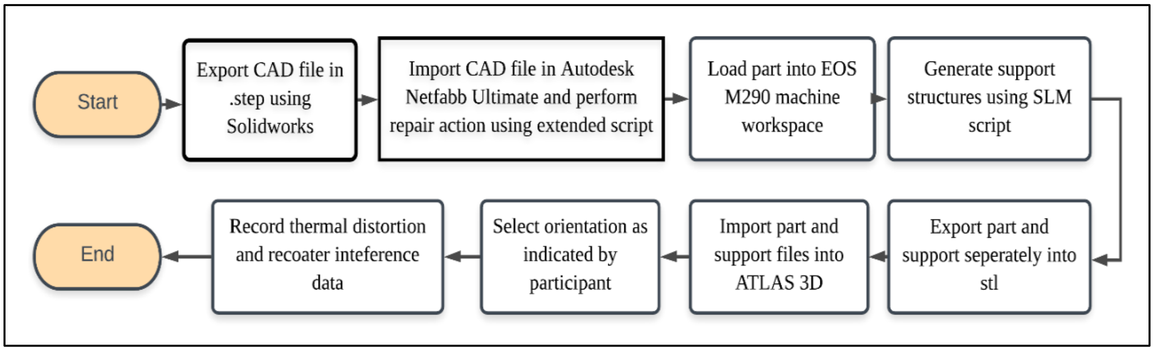


Figure 9 : CAD Data analysis flowchart

models from nine participants were processed using the similar workflow adopted in previous research for novice designers [31]. The complete process workflow is depicted in Figure 9. Support Structures are generated using the standard SLM parameter set with a support critical angle of 35° on Autodesk Netfabb Ultimate [46]. Native CAD files generated from Solidworks in .STEP format are repaired using the extended repair script from Netfabb and then arranged into the EOS M290 workspace. The default build strategy for Stainless Steel 316L with a 30 micron parameter set was selected from Netfabb library. To account for the wire EDM process, parts were raised by 1.5mm above the platform using the "Force part above platform" feature. After applying support structures with standard SLM script, the CAD model was exported to ATLAS 3D [47] for simulation to predict thermal distortion and re-coater interference. The same machine workspace and material were selected from the ATLAS 3D machine and material library. The entire process workflow was repeated for all nine participants as depicted in Figure 9. A manufacturability matrix table is generated to consolidate CAD file details, build details and simulation metrics of all nine participants.

4.4 Results

Manufacturability Matrix for the Re-designed Bracket: The primary criteria for part manufacturability (weight, build time, volume, support volume, recoater interference, thermal distortion, and strength factor) were compared for all 9 participants in contrast with the original ALCOA bracket design. The results are shown in Table 2. The criteria in the matrix are developed by the research team with anecdotal, academic and professional experience, specifically for the L-PBF process.

Table 4 : Manufacturability matrix data for N=9 designers

	Novice designers						**Expert designers**			
Criterion	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Original**
Weight (grams)	309	289	529	785	527	662	354	219	203	868
Build time estimate (hh:min)	15:56	15:44	22:17	28:51	21:28	25:27	18:06	13:12	8:04	6:42
Volume (cm^3)	39.5	36.9	68.8	101	66.1	84.63	46.4	28	25.9	110.86
Support Volume (cm^3)	2.63	2.71	4.04	3.68	2.2	3.43	4.28	2.57	2.01	3.47
Recoater interference	No	No	No	Yes	No	No	No	No	No	No
Thermal distortion (±mm)	0.58	0.75	0.92	1.17	0.77	0.76	0.59	0.56	0.97	0.81
Strength (Factor of safety)	1.21	1.21	1.86	2.48	2.00	2.71	1.77	1.03	0.75	2.14

As seen from Table 4, there is a significant difference in weight reduction results for all nine participants. To provide a better insight into assessing the design quality for each participant, a normalization approach is used to assign a rank for each resultant design. We adopted a normalization approach used by Marler et al for multi objective optimization of engineering designs[48]. In this approach, the manufacturability metrics for all nine participants are compared with the best in category and the derived value is therefore normalized. While we understand that each metric does not have the same weight (such that in some cases build time would not be equally important as support volume) assigning weight to each metric would digress the analysis to more of a quantitative approach. The normalized stacked bar chart with expert and novice participant segmentation is shown in Figure 10. As consistent with normalization approaches, the longer the bar of a participant in a certain category, the better performing the design is in that manufacturability criteria. For criteria like build time and thermal distortion, the lowest value is the best in the category, whereas for every other criteria, the highest value is the best in its category.

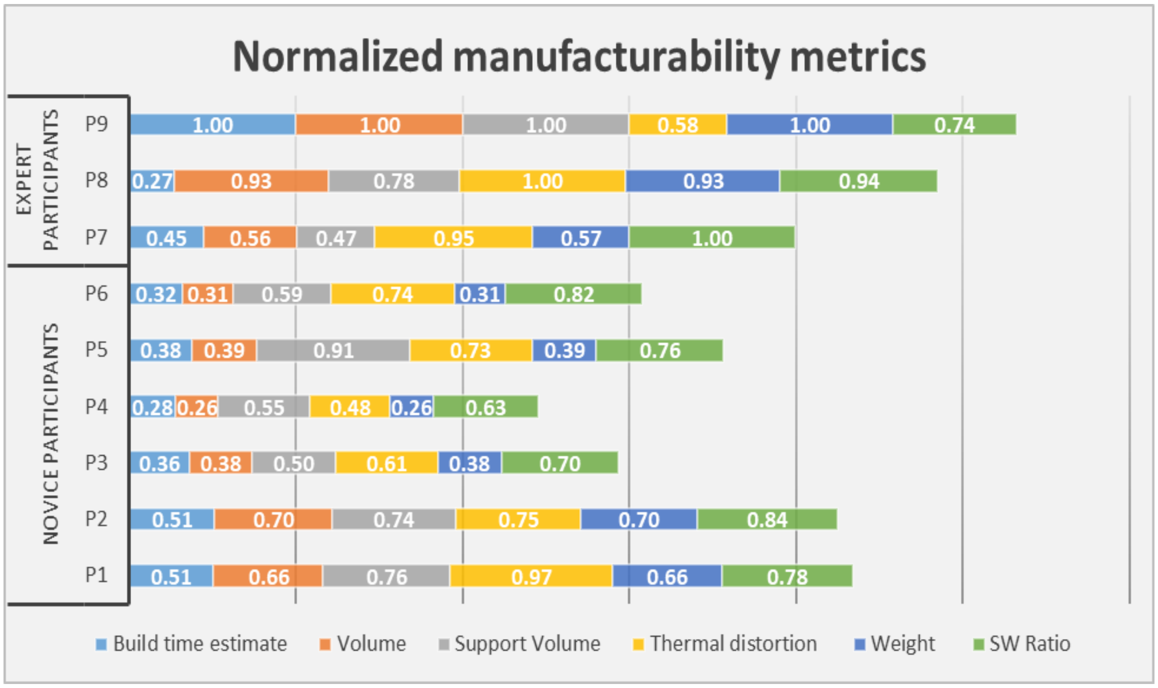


Figure 10 : Manufacturability of re-designed parts, normalized

Performance Characteristics of Novices vs Experts

The manufacturability metrics of each participant are ranked in comparison with the best in that category ranked as 1.00. For instance, Participant 9 has the lowest build time estimate, volume, support volume and weight; clearly performing best in the design challenge. On the other hand, the design generated by Participant 4 has the shortest bar length for all categories except support volume and strength to weight ratio. It can be inferred from the normalized stacked bar chart that designers P9 and P8 – both expert practitioners outperformed other participants with overall success in all metrics. Now that we know the design performance standings for all participants, it would be important to link designer behaviors with insights into time allotted to each design activity in codebook to success in manufacturability. Also, from our previous research study hypothesis, we observed that spending more time on stress analysis and problem scoping yielded better results.

Analyzing designer behaviors

The manufacturability success of a design when compared to percentage of total time spent on a given code (i.e. a given behavior as per codebook) yield interesting results. Figure 11 represents the aggregate view of the percentage of total time spent on each design activity with

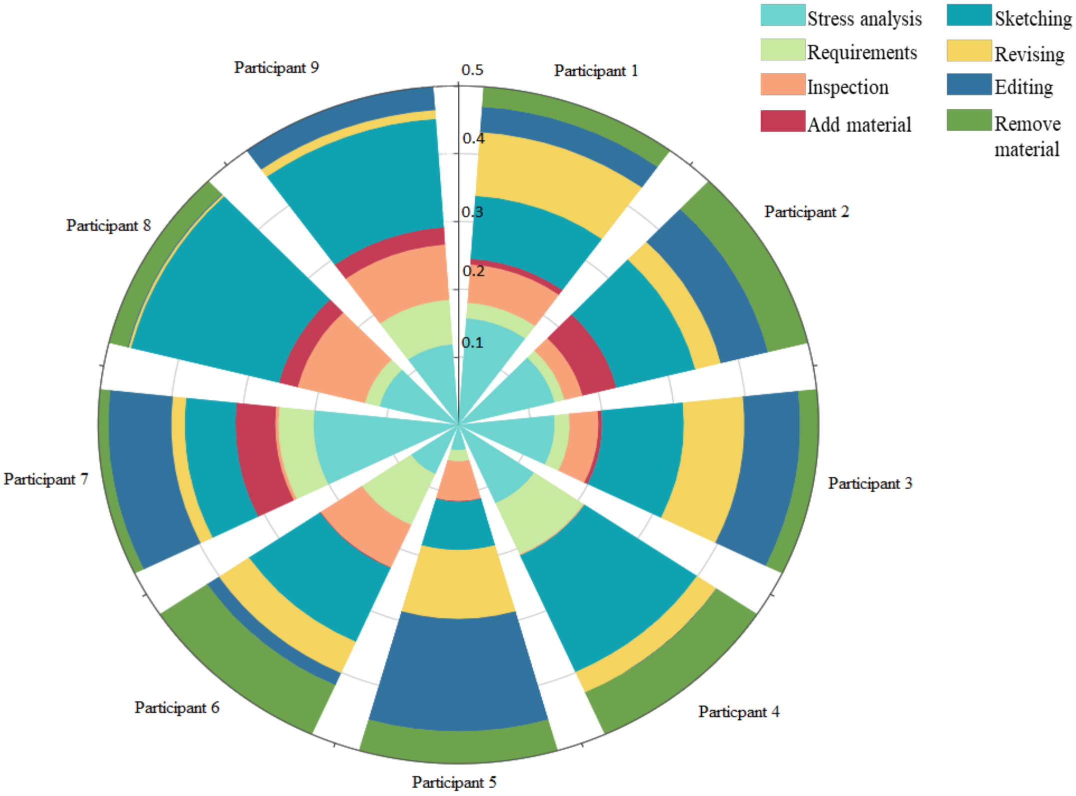


Figure 11 : Percentage of total time spent by each participant on a design activity

reference to the codebook. The index of 0.1-0.5 is the proportion of total time spent on each activity. As an example, if a designer's process involved spending 5 minutes on sketching, out of a total of 50 minutes, the behavior would be plotted at the 0.1 mark for that participant.

The expert pool of participants spent minimum time (less than 0.05%) on removal of material as opposed to most novice designers. The amount of time spent in revising existing and new modifications was significantly less as compared to the time taken by novice designers. Expert participant numbers P8 and P9 (whose designs yielded the top two results) per the normalization of design criteria spent more than 20% of their time in inspecting dimensions and problem scoping. This result coincides with existing literature about expert v/s novices [16][23][19].The percentage of time spent by both novice and expert designers on sketching related activities is around 15-45%. This finding is in line with the previous research study done by this group. Lastly, except for Participant 5, all designers spent 15% or more time on stress analysis related activities.

4.5 Discussion

Drawbacks of parametric modeling: It is observed that all participants spend 13% to 45% of their time in 2D sketching related activities. These activities primarily included generating a 2D sketch for either adding or removal of material. This finding highlights an important drawback of parametric modeling software like SolidWorks. This issue has also been highlighted in literature where it has been proven that parametric software limit capabilities of modifying a 3D model [49][50]. Incidentally, as part of response to our post design challenge survey, one of the participants commented that "SolidWorks lack of direct modeling tools (push, pull, delete face) made redesign for additive more difficult".

Unique bottom-up approach: A participant from the expert control group adopted a unique approach in re-designing the part for AM. Instead of adopting the top-down approach which involve sketching, modifying and removing material from given CAD file, the participant adopted a bottom-up approach where based on the stress analysis results, loading conditions and fixtures, he/she started designing the part from scratch. This approach was adopted by Participant 9, which in fact yielded the best results for manufacturability. Since this participant was from the expert group, there was heavy use of fillets and care to avoid sharp corners, which is a prominent characteristic of experienced designers. The design generated by Participant 9 is shown in Figure 12. From past literature with expert participants, it has been observed that apart from generating best results, experts tend to use novel strategies to approach design problems [16]. However, it cannot be inferred that this approach is the best approach possible, since the Strength to Weight ratio of Participant 9's design is 0.75, which is less than other expert practitioners.

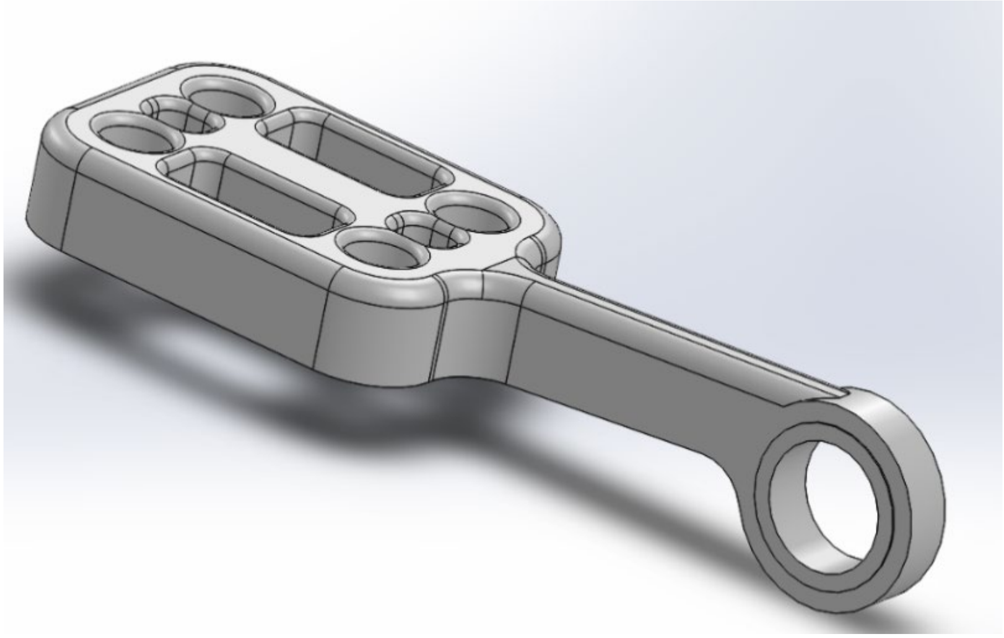


Figure 12: CAD model re-designed by Participant 9

Design engineering education: Although this is a small sample size of expert participants, there are implications from this research that will inform future research directions and practice in the Design for Additive manufacturing and design engineering education community. Built on the findings from this research study, engineering educators can teach opportunistic and restrictive DfAM concepts using a combination of stress analysis, modeling, AM programming and simulation software. It is important to note that most of the software used for this study had student and educational licenses available.

4.6 Limitations and future work

As with any qualitative analysis study, more number of participants increase the possibility of enriching data quality and research findings. Recruiting expert practitioners with DfAM education or experience was the most difficult task for this research study. With the advent of new graduate programs focused on AM [29][27], there will be a possibility of recruiting more experts to enhance the results of this study. With use of eye tracking data, it would be possible to measure cognitive workload of participants to relate amount of cognitive activity involved with each task. Future work also includes incorporating intercoder reliability, developed for time-resolved observational data by others in the research team to validate the methods developed for this research project.

4.7 Conclusion

This empirical study investigated the design process of nine engineering designers which consisted of both novice and expert practitioners. The participant behaviors were captured using screen capture and eye tracking methods. The design behaviors were qualitatively coded and compared with the final design efficacy which was measured with a manufacturability matrix developed for the L-PBF process. The manufacturability success results of all six participants are contrasted and compared using a normalization approach. Implications from this study, indicate that the re-design approach adopted by both participants differs in the amount of time spent on each design activity. Findings indicate that design success of participants who focused more on problem scoping activities tend to be higher. The most successful designs generated involved spending less time on material removal activities, which was also the key differentiator amongst results obtained from expert and novice designers. The study also highlights the drawbacks of parametric modeling software, which are not well suited for the re-design for AM process.

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Chapter 5

CONCLUSIONS AND FUTURE WORK

Design for Additive Manufacturing (DfAM) is considered to be the most important tool to help unlock the potential of freeform fabrication. Previous research efforts have systematically analyzed and synthesized the DfAM process using frameworks, checklists and worksheets. The need of the hour is to characterize the (re)Design for AM process, which is widely used by engineering designers across the aerospace, automotive and healthcare industries. This research employed experimental and qualitative research paradigms to provide a new avenue in DfAM and design engineering education research. This thesis provides the first known investigation into characterizing the re-design for AM process using constant comparative and qualitative methods with expert and novice design engineers.

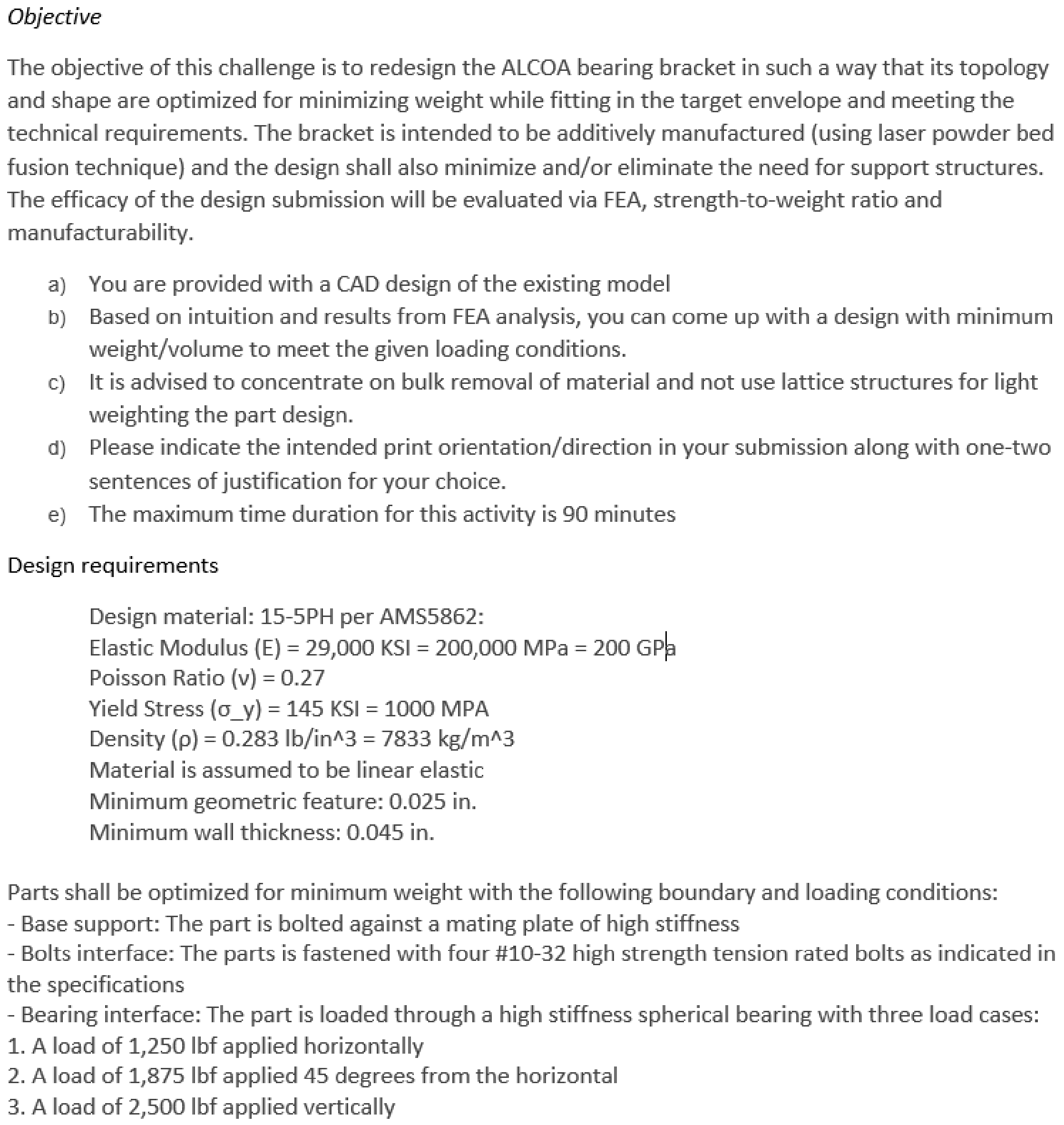
The need for graduate level AM focused programs is highlighted in Chapter 2. Engineers of the future will have to be equipped with lean design and manufacturing knowledge to tackle the ever evolving world of Additive Manufacturing, and offers opportunities for engineering education research to expand into AM. Chapter 3 seeks to address the gap in DfAM process characterization and education with an empirical study consisting of graduate students enrolled in a full time course at a large public university. The empirical study consists of a design challenge where the participants have to re-design an airplane bearing bracket considering the, constraints, opportunities and design freedom offered by AM. The design process is recorded using eye tracking and screen capture methods and the behaviors are analyzed be developing a codebook consisting of eight different design behavioral categories. The design success is measured considering the manufacturing elements of the L-PBF process and a new manufacturability matrix is presented and used to evaluate manufacturability fitness. Using content analysis methods, a connection is established between design behaviors and manufacturability success using a normalization approach. The participants spent most of their time on stress analysis and sketching related activities. Implications point toward the trend that spending more time on stress analysis related activities may result in a more effective design. The small samples size makes it difficult to claim generalizability, statistical significance or effect size. A designer centric workflow is proposed based on the learnings from the empirical study to encourage behaviors in students that correspond with manufacturability success.

Chapter 4 extended the prior empirical study with more participants with different profiles. Based on initial screening and results from a post design challenge survey, the participants were categorized as novices and experts. In this study, it was observed that the expert pool of participants spent less than 0.05% of their time on activities involving removal of material. The amount of time spent by all participants for sketching related activities range between 15-45% of the total time. All participants, except one spend more than 15% or more of their time on stress analysis related activities which re-validates the findings observed in Chapter 3.

Future work includes broadening the sample to provide more generalizable results. Further, future work includes using machine learning algorithms like Hidden Markov Models can be used to derive the sequence of activities used by each participant. It is hoped that the design behaviors of high and low performing designers can be distinguished using the state transition activity analysis. Lastly, since the coding in this study was conducted by one coder, we expect to validate this approach using interrater reliability methods developed for observational time-resolved data.

Appendix A

Design challenge prompt



Objective

The objective of this challenge is to redesign the ALCOA bearing bracket in such a way that its topology and shape are optimized for minimizing weight while fitting in the target envelope and meeting the technical requirements. The bracket is intended to be additively manufactured (using laser powder bed fusion technique) and the design shall also minimize and/or eliminate the need for support structures. The efficacy of the design submission will be evaluated via FEA, strength-to-weight ratio and manufacturability.

a) You are provided with a CAD design of the existing model
b) Based on intuition and results from FEA analysis, you can come up with a design with minimum weight/volume to meet the given loading conditions.
c) It is advised to concentrate on bulk removal of material and not use lattice structures for light weighting the part design.
d) Please indicate the intended print orientation/direction in your submission along with one-two sentences of justification for your choice.
e) The maximum time duration for this activity is 90 minutes

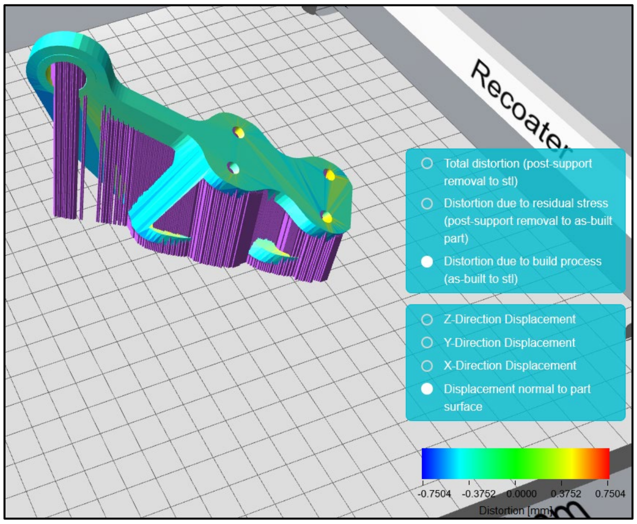
Design requirements

Design material: 15-5PH per AMS5862:
Elastic Modulus (E) = 29,000 KSI = 200,000 MPa = 200 GPa
Poisson Ratio (ν) = 0.27
Yield Stress (σ_y) = 145 KSI = 1000 MPA
Density (ρ) = 0.283 lb/in^3 = 7833 kg/m^3
Material is assumed to be linear elastic
Minimum geometric feature: 0.025 in.
Minimum wall thickness: 0.045 in.

Parts shall be optimized for minimum weight with the following boundary and loading conditions:
- Base support: The part is bolted against a mating plate of high stiffness
- Bolts interface: The parts is fastened with four #10-32 high strength tension rated bolts as indicated in the specifications
- Bearing interface: The part is loaded through a high stiffness spherical bearing with three load cases:
1. A load of 1,250 lbf applied horizontally
2. A load of 1,875 lbf applied 45 degrees from the horizontal
3. A load of 2,500 lbf applied vertically

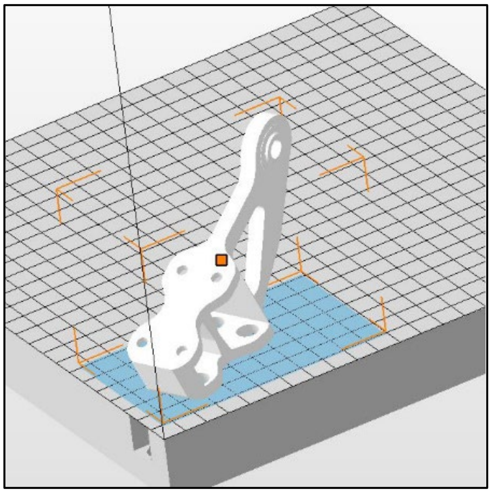
Appendix B

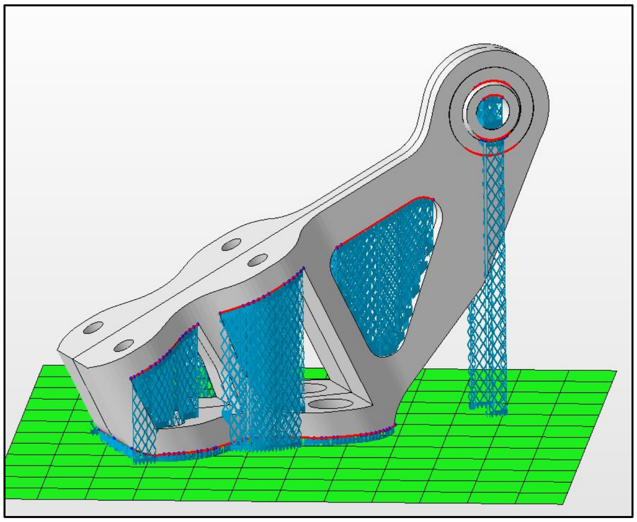
Build plan of Participant 2



○ Total distortion (post-support removal to stl)
○ Distortion due to residual stress (post-support removal to as-built part)
● Distortion due to build process (as-built to stl)

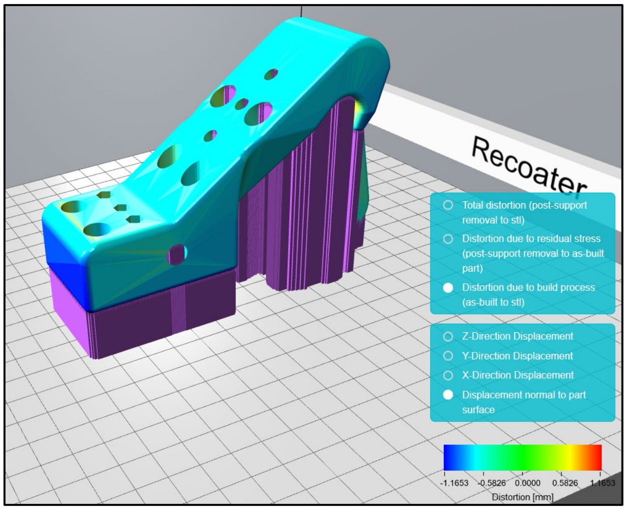
○ Z-Direction Displacement
○ Y-Direction Displacement
○ X-Direction Displacement
● Displacement normal to part surface





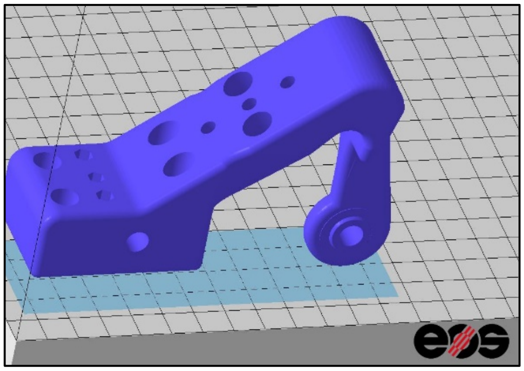
Appendix C

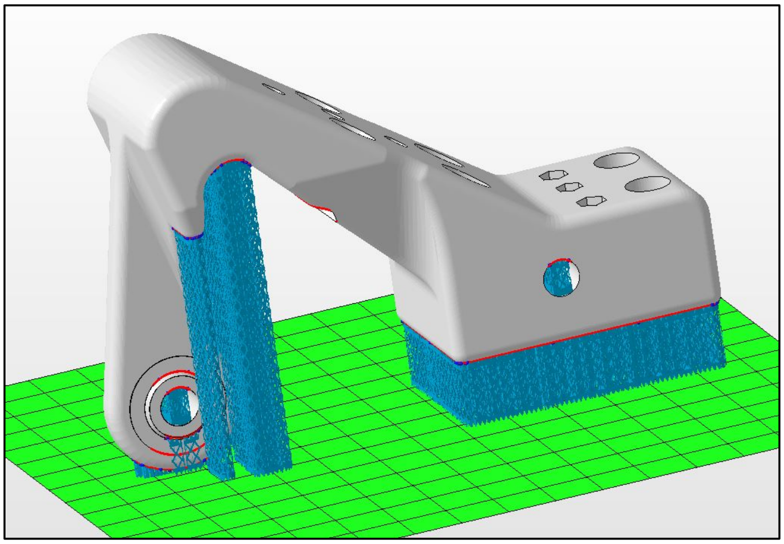
Build Plan of Participant 4



○ Total distortion (post-support removal to stl)
○ Distortion due to residual stress (post-support removal to as-built part)
● Distortion due to build process (as-built to stl)

○ Z-Direction Displacement
○ Y-Direction Displacement
○ X-Direction Displacement
● Displacement normal to part surface





Appendix D

List of Relevant Papers

Published:

Presented at the 2019 ASEE Annual Conference in Tampa, Fla.

1. Priyesh Mehta, Catherine Berdanier (2019) - A Systematic Review of Additive Manufacturing Education: Towards Engineering Education Research in AM.

Presented at the 2019 Solid Freeform Fabrication Conference in Austin, TX

2. Priyesh Mehta, Catherine Berdanier, Manoj Malviya, Colin Miller and Guha Manogharan (2019). An empirical study linking additive manufacturing designer's behaviors to success in manufacturability.

Planned submission:

1. Priyesh Mehta, Catherine Berdanier, Manoj Malviya, Colin Miller and Guha Manogharan (2019). Design for Additive Manufacturing: A comparison of novice and expert practitioner behaviors. To be submitted to *ASME Journal of Mechanical Design.*