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

Priyesh Mehta, Catherine G.P.Berdanier*, Manoj Malviya, Colin Miller and Guha Manogharan*

Department of Mechanical Engineering,
Pennsylvania State University, University Park, PA 16802

*Corresponding Author: cgb9@psu.edu

Abstract

This paper 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 paper 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.

Keywords: Design for AM, Topology Optimization, Design Framework, Eye-tracking, Manufacturability and Additive Manufacturing Education

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.

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?

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.

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 1. 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].

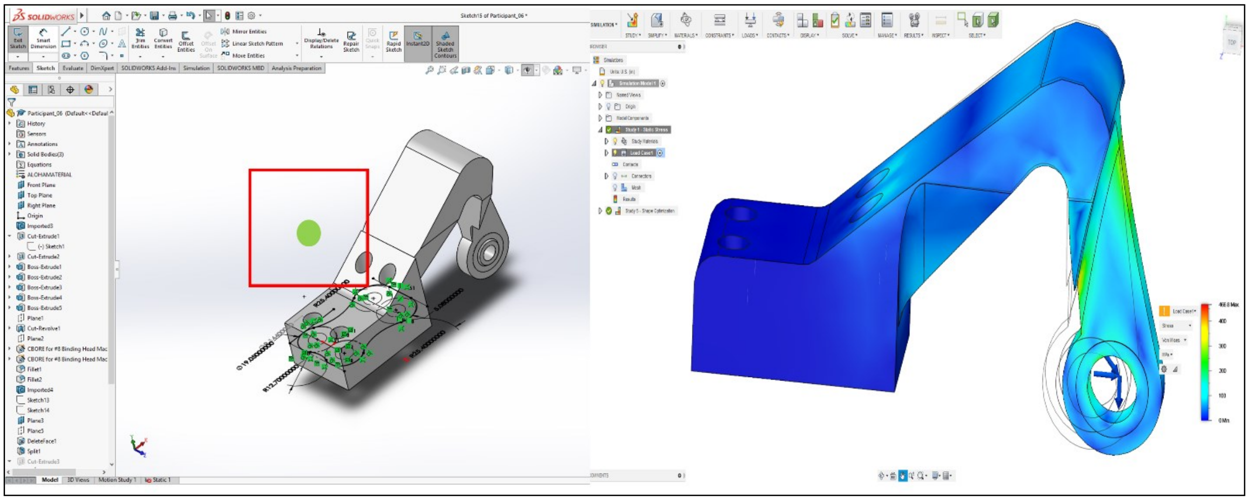


Figure 1 : With the use of gaze tracking, the participants' attention patterns were identified

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 2. 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

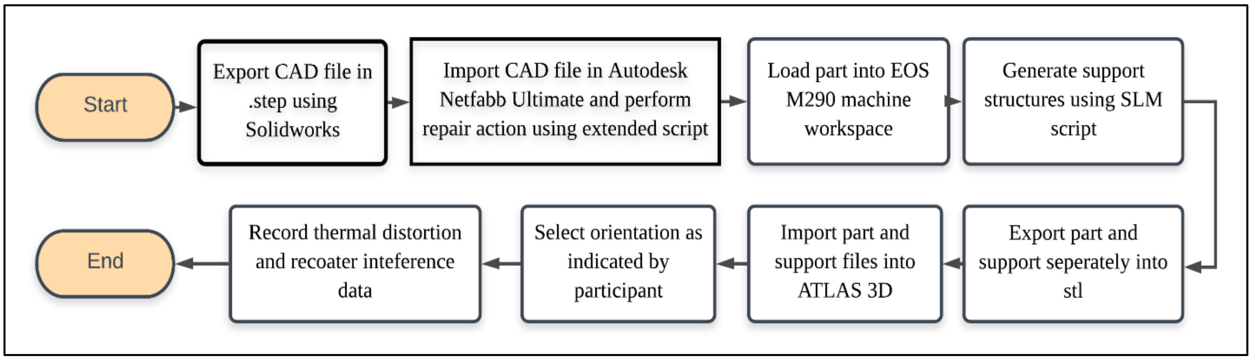


Figure 2 : **Data analysis workflow for participant-generated CAD file**

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.

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 3. The longer the bar of a participant in a certain category, the better the performance of the design in that manufacturability criteria.

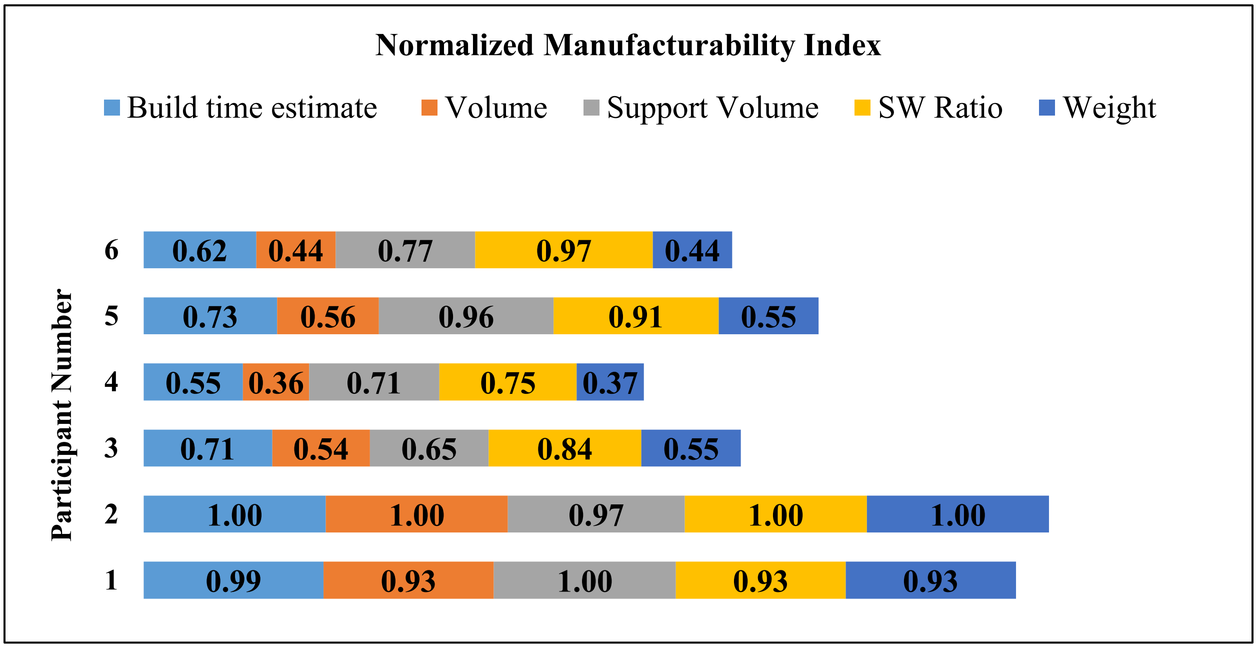


Figure 3: Normalized manufacturability analysis comparing participant designs

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. 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.

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 4 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.

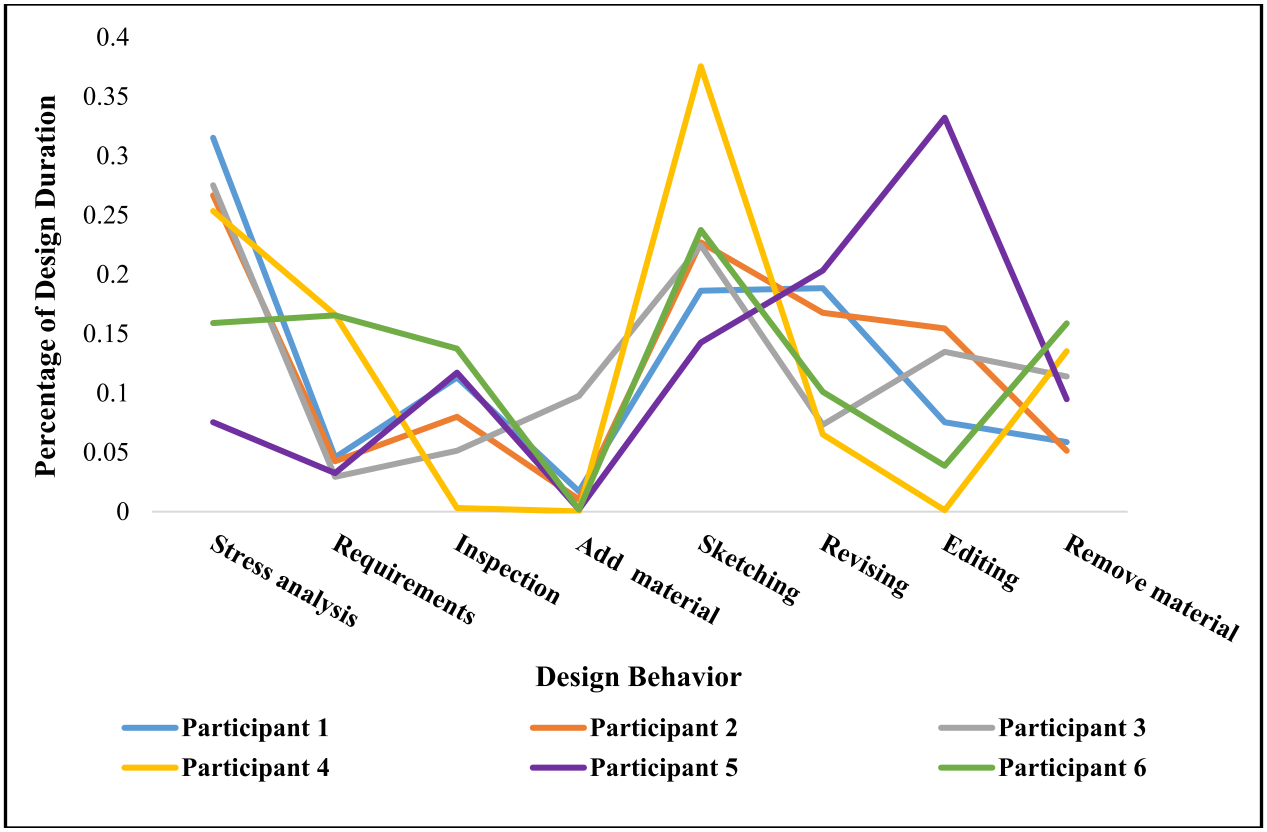


Figure 4: Percentage of total design challenge time spent on each activity

The behaviors represented in Figure 4 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.

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 5 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.

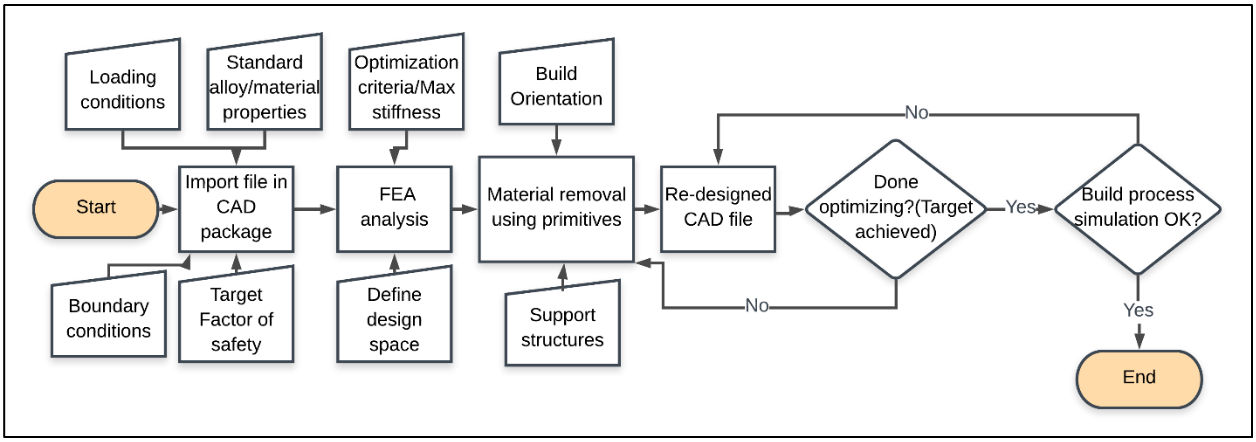


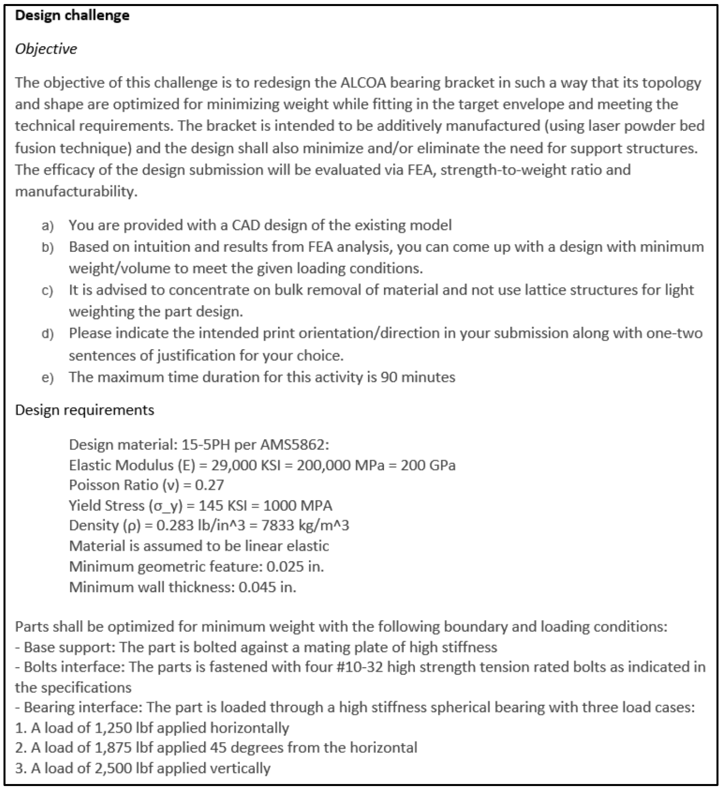
Figure 5: Proposed workflow to encourage behaviors that correspond with manufacturability in Re-design for Additive Manufacturing processes

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 conducying 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.

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.

Appendix A: Design Challenge



Design challenge

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.

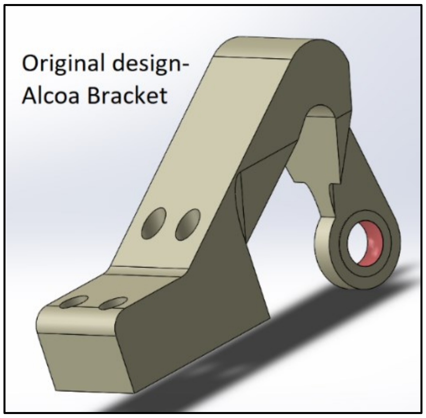
a) You are provided with a CAD design of the existing model
b) Based on intuition and results from FEA analysis, you can come up with a design with minimum weight/volume to meet the given loading conditions.
c) It is advised to concentrate on bulk removal of material and not use lattice structures for 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

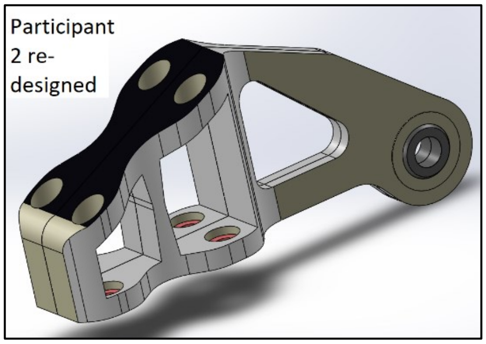
Design requirements

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: Example CAD Screenshots





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