Proceedings of the ASME 2022
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC-CIE2022
August 14-17, 2022, St. Louis, Missouri

DETC2022-91101

ASSESSING THE MANUFACTURABILITY OF STUDENTS' EARLY-STAGE DESIGNS BASED ON PREVIOUS EXPERIENCE WITH TRADITIONAL MANUFACTURING AND ADDITIVE MANUFACTURING

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ABSTRACT

As additive manufacturing (AM) becomes more mainstream in industry, the newer design for additive manufacturing (DfAM) considerations must be distinguished from the older design for traditional manufacturing (DfTM) considerations. Designers who wish to maximize additive manufacturing's potential must reconsider the traditional manufacturing axioms they may be more familiar with. While research has previously investigated the potential influences that can affect the designs produced in concept generation, little research has been done explicitly targeting the manufacturability of early-stage concepts and how previous experience in manufacturing affects this. The research in this paper addresses this gap in knowledge, specifically targeting differences in concept generation due to designer experience with additive manufacturing and traditional manufacturing. In this study, participants were given priming content on DfTM and DfAM considerations and then asked to complete a design challenge centered on concept generation. The participants' final designs were evaluated for manufacturability as suited for traditional and additive manufacturing. Results show that students with low manufacturing experience levels create designs that are more naturally suited for traditional manufacturing. Additionally, as designers' manufacturing experience levels increase, there is an increase in the number of designs suited for additive manufacturing. This correlates with a higher self-reported use of DfAM axioms in the evaluation of these designs. These results suggests that students with high manufacturing experience levels make a subconscious decision for which manufacturing process to design for.

Keywords: Additive Manufacturing, Traditional Manufacturing, Concept Generation, Experience

1. INTRODUCTION

Additive Manufacturing has rapidly advanced to become a powerful tool for developing end-use products. This new manufacturing process can produce products faster than Traditional Manufacturing, satisfying the customer's needs swiftly [1]. With the desirable cost savings that additive manufacturing can provide through benefits such as free complexity and mass customization, there is incentive for designers to expand their approach to manufacturing to encompass AM technology in addition to TM technology, such as casting, injection molding, and machining. However, the lesser restrictions and expanded design freedom that are associated with DfAM encourages designers to rethink their current designs in favor of this new domain. In rethinking their designs, considerations must be made to account for the differences between DfTM and DfAM [2]. DfTM promotes the use of simple designs and minimizing the number of parts/components to produce the design as quickly and easily as possible. In contrast, DfAM encourages the use of intricate geometric designs and functional complexity without hindering the manufacturing time and the process of assembly.

While research has explored how early-stage design interventions can help encourage DfAM use, especially regarding creativity [3, 4] and innovation [5], there is little research investigating the natural tendencies of designers to pursue either traditionally or additively manufacturable designs during concept generation. This is an important area to investigate because any concepts that are prematurely discarded or avoided in early-stage design due to their perceived infeasibility [6] may be feasible when looking at all possible methods to produce the design. As such, research is needed to determine if the designers' early concepts are better suited for TM or AM, and how their previous experiences with manufacturing influence this underlying tendency. This focus of both traditional and additive processes allows us to understand what designers are inherently designing for and see whether their self-evaluation of the design's manufacturability changes based on their previous experience.

2. LITERATURE REVIEW

To properly contextualize the research in this paper, it is first important to understand the roles of expertise and content priming within concept generation (Section 2.1), and how DfAM challenges existing notions of manufacturability, especially in early-stage design (Section 2.2).

2.1 The Role of Expertise and Content Priming in Concept Generation

Expertise is a significant factor that contributes to a designers' creativity and the types of designs they produce. Expertise can come from gaining experience in settings such as a job or in a classroom. Previous experience relating to a relevant domain can enable a designer to create novel ideas that novices without experience cannot [7]. Expertise can also impact the concept generation phase negatively, as designers with previous experience can prematurely discard ideas created in the brainstorm period based on intuition of infeasible solutions [8]. This practice is discouraged, as using the brainstorm period to create as many designs as possible yields greater creativity and better performance [9]. The ideas produced in a concept generation phase can be impacted by many factors, with the designers' previous experience representing the strongest influence. These factors result in designers developing advanced ideas while also discarding potentially viable concepts.

In contrast to professionals in the industry, novices may lack the previous experience that aids in the decision-making process. Cross [10] extensively studied the differences between experts and novices, where it was found that novices had difficulty setting up and defining the problem statement and would have their cognitive activity decline in working through an experiment. Ahmed et al. [11] found that novices expressed uncertainty in their design decisions, resorting to using trial-and-error methods as opposed to strategizing early in the design process, and expressed difficulty working with the unfamiliar task. The work by Cross and Ahmed indicates that providing design tools to students can help them work through the design process. By providing students with content to help influence their design decision-making, they can develop designs that reflects those created by experts. In developing these novel ideas, the designer (regardless of whether they are a novice or an expert) can use design heuristics such as geometry modification, design flexibility, and functional adaptivity [12].

Designers can be primed to solve a design problem based on the material that is provided to them. During this priming process, information is brought to the forefront of the designers' minds. This priming process enables people to retrieve older information while retaining any newly introduced information, as was found by Ratcliff [13], Tulving [14], and Schacter [15]. Likewise, Bonnardel et al. [16] showed from their testing that it is possible to prime designers with specific content, with the impact of priming varying based on the individuals' previous experience. Priming designers prior to concept generation activities can help align their designs to better reflect the priming content. For example, Yilmaz et al. [17] found that introducing priming content early in the design process is an effective way to produce creative and diverse designs. In addition, Lauff et al. [18] found that when priming students with additive manufacturing content, students create higher quality designs. Priming can be used as an effective tool to frame students to create designs that relate to the priming content. By incorporating Design for Manufacturing (DfM)-related priming into design work, the participants can choose what they want to incorporate into their designs, rather than sub-consciously forgetting about them when they need to be recalled.

2.2 Consideration of Design for Additive Manufacturing within Concept Generation

Due to the distinct differences between DfTM and DfAM concepts, significant research is being performed toward generating content appropriate to act as priming in design activities. As an example, Laverne et al. [19] developed priming content for additive manufacturing's design considerations, which can be categorized into three groups: Opportunistic-DfAM, Restrictive-DfAM, and Dual-DfAM. Opportunistic-DfAM (O-DfAM) refers to the capabilities of additive manufacturing such as geometric complexity and topology optimization, while Restrictive-DfAM (R-DfAM) refers to the limitations of additive manufacturing such as material selection and machine constraints.

With this DfAM priming content, researchers are exploring how such content impacts the outcomes of design activities, especially in early-stage design. Previous research has shown that students who are primed with either O-DfAM or R-DfAM results in framing students to create designs that are not ideal for AM [3]. For creating designs that are ideal for additive manufacturing based on framing, students must be introduced to both O-DfAM and R-DfAM together in a Dual-DfAM format. To test the effects of AM priming on students designs, Prabhu et al. [3, 4, 20, 21], developed priming content based on Laverne's categorization and studied its effects on undergraduate students' concept generation. In his experiments, three groups of students were given a design challenge along with either (1) no-DfAM priming content, (2) only R-DfAM, or (3) Dual-DfAM. The results showed that students primed with only R-DfAM emphasized a design objective of minimizing build time, while students primed with Dual-DfAM emphasized a design objective of minimizing build material [20]. Additionally, designs generated by the R-DfAM group incorporate more appropriate tolerances with easily accessible support material but also tend to have higher build plate contact area when compared with designs from the Dual-DfAM priming [21]. Further, participants from all three groups reported higher use of restrictive DfAM axioms, compared with opportunistic DfAM axioms [5].

While Prabhu researched the effects of AM priming on the additive manufacturability of designs [3], results do not account for the design's manufacturability through TM and their associated design considerations [22]. While some of these designs reflect the design considerations associated with additive manufacturing, an evaluation for traditional manufacturing has not yet been done. These design considerations, which focus on the simplicity of the designs, are likely to be present given the designer's previous experience and interpretation of any provided priming content. Currently, there is a lack of research on the manufacturability of designs when evaluating for TM and AM, which this paper investigates. By evaluating the designs in terms of manufacturability for either TM or AM with priming content to invigorate their minds for creative thinking, the effects of previous manufacturing experience can be better assessed.

3. RESEARCH OBJECTIVES

The objective of this paper is to determine whether there is an impact on the types of designs produced through concept generation based on designers' previous experiences with TM and/or AM. Further, the work seeks to understand how designers self-report their use of different DfTM and DfAM axioms in their designs, as derived from given priming content. Through this investigation, this work will understand how experience affects whether designs are inherently more suitable for TM (typically simplistic) or AM (typically complex). The following research questions are proposed:

(1) *How does manufacturing experience affect the manufacturability of the designs when evaluated for traditional manufacturing and additive manufacturing?*

We hypothesize that designs from students at a low experience level will tend toward traditional manufacturing. This claim assumes that all the participants in this study, regardless of their self-reported formal DfM experience levels, have extensive informal experience with traditional manufacturing. With over 70% of the manufacturing businesses in the US utilizing Computer Numerical Controlled (CNC) machining [23], this current dominance in technological manufacturing leads to more products today being produced using traditional manufacturing. The exposure to the products made from traditional manufacturing causes the participants to be informally trained in the design considerations used to make them. As experience increases in either type of manufacturing, the resulting designs will likewise increase in that type of manufacturability (i.e., higher experience in DfAM will lead to designs that are more suitable for AM).

(2) *How does manufacturing experience affect the students' self-reporting of the designs' manufacturability?*

We hypothesize that students with low experience levels will report few DfM axioms in their designs. This claim is again justified by the exposure to traditionally manufactured parts based on their technological dominance [23]. With students being exposed to traditionally manufactured products such as CNC machined-wooden desks and injection-molded plastic containers, the students are informally exposed to the axioms used to make these products. As the experience increases in either type of manufacturing, they will be more familiar and confident with the axioms, and therefore recognize more axioms in their designs.

4. EXPERIMENTAL METHODS

To answer the research questions, an experiment was developed to test the effects of previous experience on the students' generated designs. The experiment consisted of three stages: (1) a pre-intervention survey, (2) manufacturing priming, and (3) a design challenge followed by a self-evaluation on the design. The study was reviewed and approved by the Institutional Review Board, and implied consent was obtained from the participants prior to the experimentation. In this experiment, the participants would first provide their current level of expertise with traditional manufacturing and additive manufacturing. Next, they would receive priming content for both manufacturing technologies to bring these concepts to the forefront of their minds. From there, they were asked to complete an open-ended, manufacturing-agnostic design challenge. They then completed the experiment by self-evaluating their designs for traditional manufacturing and additive manufacturing based on the axioms presented in the initial content priming. Finally, after the design activity, participant designs were evaluated by manufacturing domain experts. The following subsections discuss the further details behind experimentation and analysis.

4.1 Participants

Participants come from several engineering design courses at a large northeastern university. To cover a sample with varying levels of expertise, participants consisted of 46 students in a third-year undergraduate mechanical engineering design course, 32 students in a fourth-year undergraduate engineering design course, and 13 students in a graduate-level design for additive manufacturing course. Some participants' data (not previously listed) were removed from consideration due to incompleteness in the activity where key information was critical (i.e., the self-reported evaluation for the design considering the manufacturing size) or the key information was not filled in properly (i.e., the self-reported evaluation for avoiding large, flat regions had two scores filled in when only one was requested). The experiment was implemented during the middle of the Fall 2021 semester to allow students to gain manufacturing experience in their respective classes prior to the experiment's additional TM and AM priming.

4.2 Procedure and Metrics

4.2.1 Pre-Intervention Survey

At the outset of the activity, participants were given 5 minutes to complete a survey that asked about their previous experience with traditional manufacturing and additive manufacturing. They were also asked to evaluate their familiarity with a series of 14 different DfTM and DfAM axioms (7 for each) on a 5-point Likert-type scale [24], with a score of 1 representing "Never heard about it" and a score of 5 representing "Could regularly integrate it with my design process." This survey, which was modified from the studies done by Prabhu et al. [4, 20], provides an understanding of participants' current levels of TM and AM experience and confidence with their respective axioms.

4.2.2 Manufacturing Priming

After completing the pre-intervention survey, the students received a 20-minute lecture on design for manufacturing, encompassing both traditional processes and additive processes. Due to the wide range of available TM processes, casting, injection molding, machining, and sheet metal forming were used as representative TM processes. The lecture began by defining the concept of designing for manufacturing, which was followed by a brief overview of the two types of design for manufacturing axioms (DfTM & DfAM) relevant to this research. The ensuing lecture discussed in detail fundamental design considerations (restrictive and unrestrictive) for both manufacturing processes. To keep the experiment balanced, seven axioms were identified for each process (resulting in 14 manufacturing axioms to discuss). Each axiom was presented on its own separate slide, with a one-sentence summary and visual content comprising each slide. The time given to discuss both sets of axioms was balanced.

Traditional manufacturing was first introduced, where the following principles [25] were discussed: reducing part count, relying on low-labor-cost operations, avoiding intricate shapes, utilizing standard materials, components, and tooling, avoiding sharp corners by using fillets, using a uniform wall thickness, and having ample spacing between holes. Next, additive manufacturing was introduced, where the following principles [21] were discussed: incorporating complex shapes and geometries, combining multiple parts into a single part or assembly, avoiding large, flat regions, orienting overhanging surfaces, considering the minimum feature size, orienting curved surfaces, and accounting for potential variations in material properties. Examples of the content used for the manufacturing priming for traditional manufacturing and additive manufacturing are shown in Figures 1 and 2, respectively.

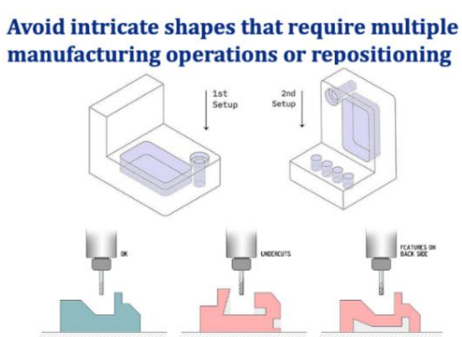


Figure 1. Sample Traditional Manufacturing Priming Content

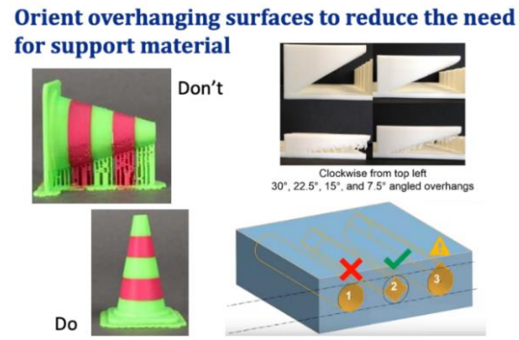


Figure 2. Sample Additive Manufacturing Priming Content

4.2.3 Design Challenge and Procedure

Following the lecture, students were given the design prompt that they would be solving. The provided design prompt was as follows. "*You are tasked with designing a solution to hold three hollow tubes securely in place and parallel to each other. All tubes must be held 2 inches away from a fixed wall (measuring from the wall to the closest edge of the tubes). The tubes are 1 inch in diameter and 3 inches long*." To accompany this text description, participants were also presented with the visuals seen in Figure 3. This design challenge was previously used by Prabhu et al. [26]. and was selected for this study because its open-ended nature creates a wide design space [26] allowing for solutions that can be produced using both traditional manufacturing and additive manufacturing. Additionally, the design challenge falls in line with the shift towards problem-based learning [27]. To remove any manufacturing biases in the design challenge, students did not receive any manufacturing constraints in the design prompt.

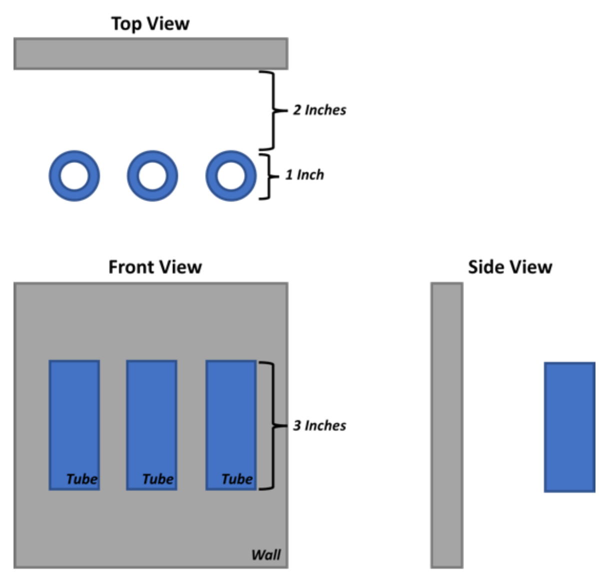


Figure 3. Design Challenge Visual Provided to Participants

After reading through the design challenge prompt, students spent 10 minutes using the provided design sheets to individually create as many solutions as possible. They were instructed to use both sketches as well as text to illustrate their designed solutions. While the students were creating designs in the concept generation session, they were also asked to describe the advantages and disadvantages of each design concept. An example of a completed design sheet is shown in Figure 4.

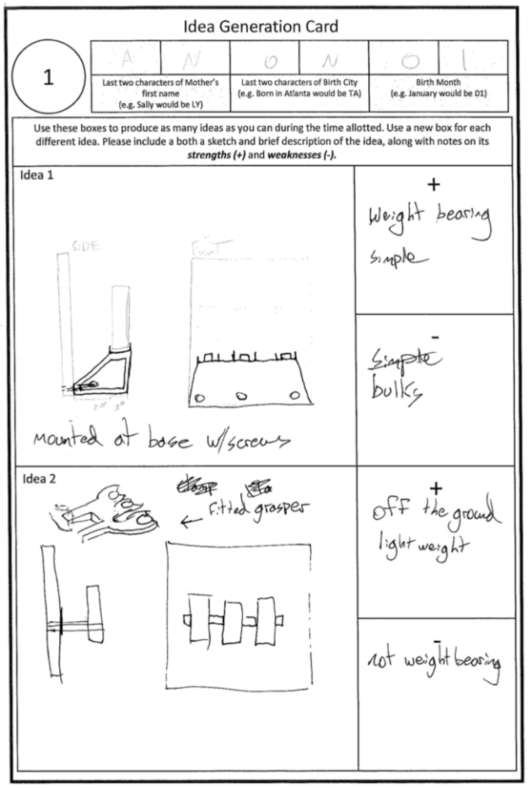


Figure 4. Example of Completed Design Sheet

Following the concept generation session, participants were given 7 minutes to identify a final design. They were informed that their final design could be any of the following: a reused or modified design from the initial concept generation period, a combination of any of the previous designs, or an entirely new idea. These points were emphasized to ensure the students were aware of all possible options and used their creativity in developing their final designs. As with the initial concept generation session, participants were asked to list the advantages and disadvantages of their final design.

After identifying their final design and discussing its strengths and weaknesses, participants were asked to evaluate their solution as designed based on the 7 DFTM axioms and 7 DfAM axioms presented in the priming content to the best of their ability. Specifically, participants were presented with each axiom and asked, "*To what extent do you agree with the following statements about manufacturing as they apply to your final design?*" They then evaluated the design using a 5-point Likert scale, where 1 represented Strongly Disagree and 5 represented Strongly Agree. This self-evaluation allows the researchers to observe which priming content principles influenced the students' designs.

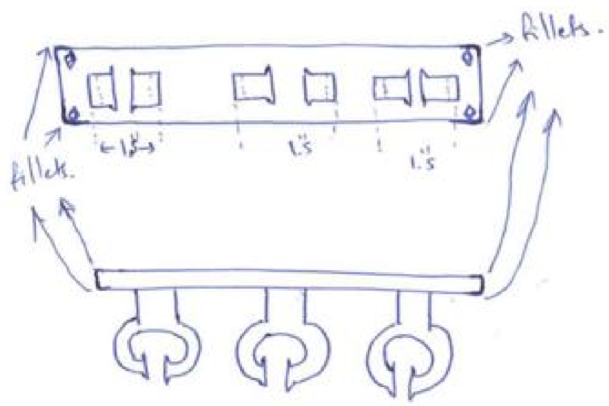
4.2 Expert Design Evaluation

To evaluate participants' final designs, three raters (two experts and one quasi-expert in design for manufacturing processes) used the Consensual Assessment Technique (CAT) as developed by Amabile [28]. This technique has expert judges evaluate creativity in their specialty domain [29]. Pertinent to the research in this paper, the CAT has also previously been used to evaluate suitability of design concepts for manufacturing [26, 30]. Both expert raters have graduate degrees, had at least 6 years of experience with creating and evaluating designs for additive manufacturing, and previously published papers in the relevant field. The quasi-expert is currently progressing through graduate coursework and has experience with creating and evaluating designs for additive manufacturing. The three raters evaluated the final designs based on both their traditional manufacturability and additive manufacturability. Both categories were evaluated on a 1-6 scale, with higher scores indicating greater suitability for that manufacturing process type. A brief description of each category is as follows:

- <u>*Traditional manufacturability*</u>: The suitability of the design for traditional manufacturing based on expert assessment. The category here focuses on the use of traditional manufacturing principles in the design. Though a variety of traditional process are possible, scoring is based on the assessment of general DfM principles applicable to a range of process types. A higher score represents a design that utilizes the principles of TM (simple shapes, rounded corners, ample spacing between holes, etc.) while a lower score represents a design that is either very difficult or impossible to manufacture using traditional manufacturing processes.
- <u>*Additive manufacturability*</u>: The suitability of the design for additive manufacturing based on expert assessment. The category here focuses on the use of both R-DfAM and O-DfAM principles in the design. A higher score represents the use of most R-DfAM and O-DfAM principles, while a lower score represents little to no identifiable R-DfAM and O-DfAM principles. Intermediate scores tend to exhibit suitable R-DfAM, but lack in O-DfAM.

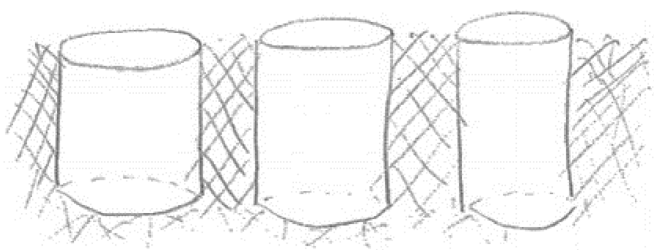
The three raters first scored 10 submitted designs together to establish the evaluation criteria and have general agreement. Next, each rater individually scored the same 40 designs which were then compared for consistency. The scores were validated for consistency using the interclass coefficient (ICC) [31, 32, 33]. The ICC value was calculated using SPSS v.28, which yielded a strong general agreement with a Cronbach's alpha (α) of 0.786 for the traditional manufacturability rating and an α of 0.782 for the additive manufacturability rating, both of which exceed the minimum threshold for meaningful agreement of 0.75 [34]. These α values were also significant with a p-value of <0.001 using a 95% confidence interval. This means that for each design the raters were giving comparable scores. From there, the raters scored the remaining designs individually. The cumulative α values across the three raters for traditional manufacturability was 0.807 and the additive manufacturability rating was 0.767, both of which were significant with a p-value of <0.001 using a 95% confidence interval. This indicates a good agreement between the raters.

After the raters evaluated all the designs, the average TM CAT score and average AM CAT score were calculated for each student by averaging the respective CAT scores provided by the raters. To more easily determine whether each individual design was better suited for one manufacturing process over another, the difference between the traditional manufacturability score and additive manufacturability score was computed. Here, this value is referred to as the ΔCAT score. Examples of designs that received a high TM score and a high AM score are shown in Figures 5 and 6, respectively.



Average TM CAT Score	Average AM CAT Score	ΔCAT Score
4.33	2.67	1.67

Figure 5. Design Example with High TM Score



Average TM CAT Score	Average AM CAT Score	ΔCAT Score
2.00	4.67	-2.67

Figure 6. Design Example with High AM Score

5. RESULTS

To communicate key data collected through this study, this section first details the distribution of students' manufacturing experience (Section 5.1), followed by statistical analysis using SPSS v.28 to answer the research questions posed for expert evaluation of manufacturability (Section 5.2) and self-reported use of DfM axioms (Section 5.3).

5.1 Distribution of Student Manufacturing Experience

Before analyzing the manufacturability of the participants' designs, it is first necessary to observe the distribution of the participants' experience with manufacturing. Table 1 shows the students' manufacturing experience distribution for both TM and AM processes. The student distribution shows that at each experience level, there was approximately the same number of students with the requisite TM experience and AM experience. Most participants claimed an experience level between 2 and 3 for both TM and AM processes.

Table 1. Student Manufacturing Experience Distribution

Experience Level	Number of Students (TM)	Number of Students (AM)
1	4	4
2	39	40
3	29	31
4	17	13
5	2	3
Total	**91**	**91**

The similarity in experience scores between both TM and AM processes prompted an additional analysis to see if there was a correlation between a participant's traditional manufacturing experience and additive manufacturing experience. Figure 7 collects the paired experience scores for each individual participant. This figure suggests that there is an interconnectedness between a participant's previous experience with TM and their previous experience with AM.

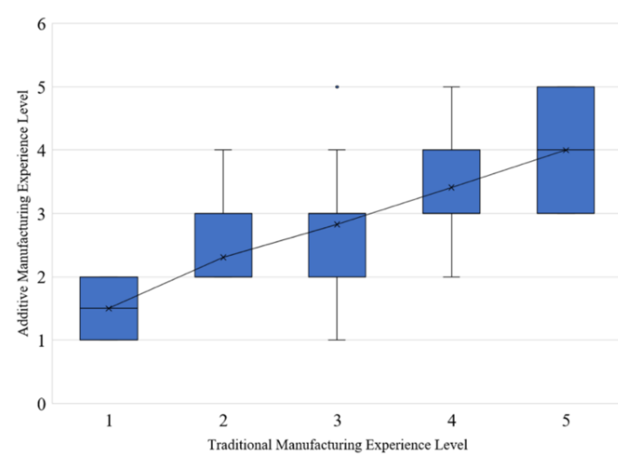


Figure 7. Manufacturing Experience Comparison

To verify the presence of a significant relationship for participants' manufacturing experiences, a Pearson R correlation test was performed. The test yielded an R-value of 0.578, signifying a positive correlation between a person's traditional manufacturing experience level and additive manufacturing experience level. Using a 95% confidence interval, this claim was verified by the statistically significant p-value of <0.001. This means that a student with a high traditional manufacturing experience level is very likely to have a high additive manufacturing experience level. The significance of this correlation and its effect on the rest of the findings will be discussed in Section 6.

5.2 Expert Evaluation of Design Manufacturability

To answer the first research question, the participants' manufacturing experience in each process, as collected earlier in Table 1, was used as the basis to compare to the difference in the manufacturability score between TM and AM (referred to as ΔCAT). The plot in Figure 8 shows changes in this ΔCAT value as manufacturing experience increases. Note that a higher ΔCAT value denotes designs that are more suitable for traditional manufacturing, while a lower ΔCAT value denotes designs that are more suitable for additive manufacturing.

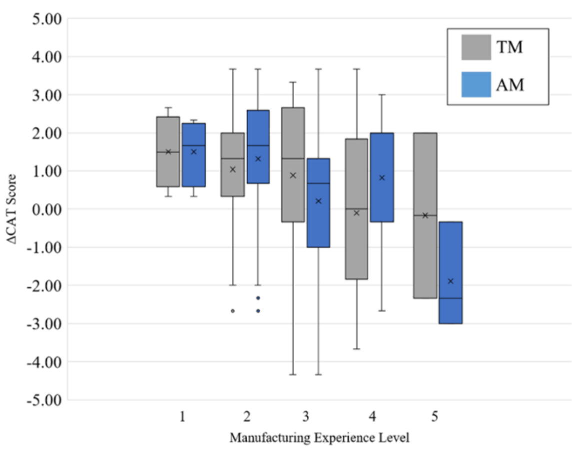


Figure 8. ΔCAT Score vs Manufacturing Experience

To test for statistical significance, a one-way ANOVA test was performed to compare the results across manufacturing experience levels. The manufacturing experience in each respective process (TM and AM) was set as the independent variable, while the ΔCAT score was set as the dependent variable. The experience level data was treated as categorical due to the clear separation between levels. Additionally, the ΔCAT values were treated as interval because there was significant meaning in manufacturability scores in-between the raters' evaluation (more specifically, a ΔCAT score of 2.5 was possible and important). A 95% confidence interval was used to determine statistical significance (i.e., $p<0.05$). The ANOVA test was chosen because the manufacturability scores were normally distributed across most experience levels as assessed by the Shapiro-Wilk test. Despite the scores not being normally distributed for students with a manufacturing experience level of 2, the ANOVA test was performed, given that all remaining experience levels were normally distributed. The p-values from these tests are shown in Table 2.

Table 2. ΔCAT Score Statistical Significance

Case	Two-Tailed P-Value	F-Value
TM Experience vs ΔCAT Score	0.220	1.465
AM Experience vs ΔCAT Score	0009	3.597

As these results show, there is a statistically significant difference in ΔCAT scores with respect to AM experience levels. To identify where this significant difference is occurring within the AM experience data, a Games-Howell post hoc was conducted for each of the experience pairs within the entire data set. A 95% confidence interval was used to determine statistical significance (i.e., $p<0.05$). This test was selected because the comparisons between experience levels was uneven (e.g., 40 participants who reported having an additive manufacturing experience level of 2 were compared with 31 participants who reported having an additive manufacturing experience level of 3). The results for the AM experience pair combinations are shown in Table 3 for additive manufacturing.

Table 3. Statistical Significance for Additive Manufacturing Levels

Experience Level Pairwise Comparison	Two-Tailed P-Value
1 vs 2	0.996
1 vs 3	0.249
1 vs 4	0.843
1 vs 5	0.117
2 vs 3	0.103
2 vs 4	0.900
2 vs 5	0.148
3 vs 4	0.856
3 vs 5	0.323
4 vs 5	0.190

The results from Table 3 show that despite general significance for all the additive manufacturing experience levels to the ΔCAT scores, the pairwise comparisons across each experience level yielded no significant differences observed. This means that the differences observed between the additive manufacturing experience and the ΔCAT scores was significant only across the cumulative samples, not at the individual level comparisons. This may be attributed to the sample size at each additive manufacturing experience level. Despite gathering a total of 91 participants, the additive manufacturing experience levels of 1, 4, and 5 had a sample size of 13 or less. More participants would be needed at these experience levels to test for pairwise comparisons at the individual levels, as the current data indicates a general difference observed with an increase in experience.

5.3 Self-Reported Use of DfM Axioms

To answer the second research question, the participants' evaluation sheets were categorized based on their identified experience levels with both traditional manufacturing and additive manufacturing. Next, the data was recorded for what Likert score they assigned to each of the 14 DfM axioms presented in the priming content. To test for statistical significance, a one-way ANOVA was performed on the data, which compared the independent variables (manufacturing experience) to the dependent variables (self-reported score for each axiom). A 95% confidence interval was used to determine statistical significance (i.e., $p<0.05$). Despite the data's violation of normality based on the Shaprio-Wilk test, the ANOVA was performed, given the robustness of the ANOVA to deviations from normality. The p-values from these tests are shown in Tables 4 and 5 for traditional manufacturing axioms and additive manufacturing axioms, respectively.

Table 4. P-values for DfTM Axiom Statistical Significance

DfTM Axiom	P-value based on TM Experience	F-Value	P-value based on AM Experience	F-Value
Reduce Part Count	0.672	0.588	0.818	0.386
Low-Labor-Cost Operations	0.640	0.634	0.833	0.364
Avoids Intricate Shapes	0.952	0.171	0.556	0.758
Standard Materials, Components, and Tooling	0.897	0.269	0.865	0.319
Avoiding Sharp Corners and Using Fillets	0.157	1.7	0.354	1.116
Uniform Wall Thickness	0.067*	2.284	0.433	0.962
Ample Spacing Between Holes	0.799	0.413	0.904	0.257

*: p<0.1

Table 5. P-values for DfAM Axiom Statistical Significance

DfAM Axiom	P-value based on TM Experience	F-Value	P-value based on AM Experience	F-Value
Complex Shapes and Geometries	0.303	1.232	0.062*	2.338
Combining Multiple Parts into a Single Product or Assembly	0.136	1.801	0.012**	3.42
Avoiding Large, Flat Regions	0.009**	3.646	0.002**	4.48
Orienting Overhanging Surfaces	0.063*	2.322	0.080	2.164
Considering the Minimum Feature Size	0.130	1.831	0.004**	4.139
Orienting Curved Surfaces	0.408	1.008	0.117	1.905
Variations in Material Properties	0.046**	2.534	0.595	0.698

*: p<0.1 **: p<0.05

With the statistically significant cases observed, a Games-Howell post-hoc test was then used to determine which experience levels were statistically significant. This test was selected because the comparisons between experience levels was uneven (e.g., 40 participants who reported having an AM experience level of 2 were compared with 31 participants who reported having an AM experience level of 3). The results were plotted and analyzed for statistical significance. Here, DfM axioms that are statistically significant at the 0.05 level will be presented, which consists of "*Avoiding large, flat regions*" with respect to both traditional manufacturing experience and additive manufacturing experience (Figure 9), "*Combining multiple parts into a single product or assembly*" with respect to additive manufacturing (Figure 10), and "*Considering the minimum feature size*" with respect to additive manufacturing (Figure 11).

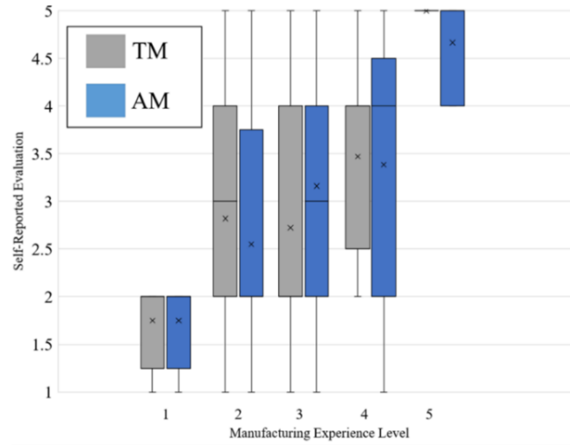


Figure 9. Avoiding Large, Flat Regions

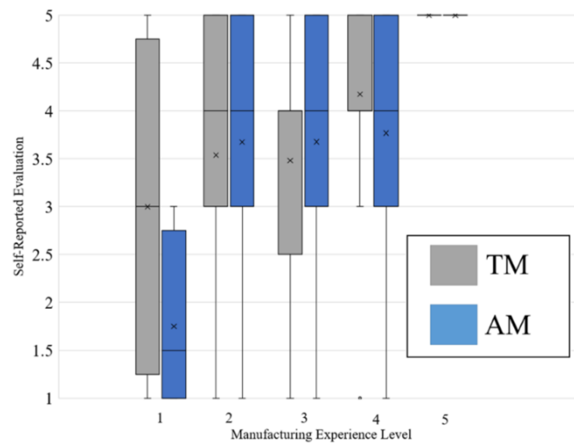


Figure 10. Combining Multiple Parts into a Single Product or Assembly

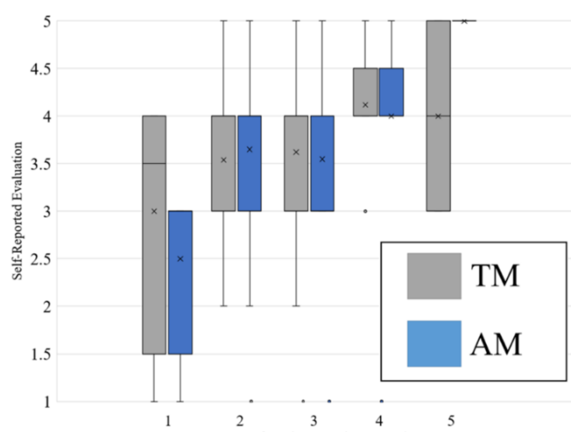


Figure 11. Considering the Minimum Feature Size

Figures 9-11 demonstrate the effects of possessing some manufacturing experience on the self-reporting of DfAM axioms. In all three showcased axioms, the self-reported scores were very low for students who identified as having minimal manufacturing experience. By increasing in experience level from 1 to 2, the self-reported scores all dramatically improved. This demonstrates that having some experience with manufacturing causes students to create, recognize, and identify DfAM axioms in their designs. As manufacturing levels increase, the self-reported scores remain relatively consistent, with an additional increase in the self-reported score at the highest experience level. This means that the middle experience levels (2-4) are incorporating aspects of the DfAM axioms into their designs, affecting the manufacturability scores distribution as shown in Figure 8. In contrast, students at the highest experience level are self-reporting DfAM axioms that are improving the design's additive manufacturability scores.

6. DISCUSSION

Based on the experimental results, there are several key findings that merit more in-depth discussion:

- At low manufacturing experience levels, participants produced designs that are more suited for traditional manufacturing.
- As additive manufacturing experience increases, the number of designs suited for additive manufacturing likewise increases.
- As manufacturing experience increases, more students report the use of DfAM axioms in their designs.

6.1 Students' designs are more suited for traditional manufacturing at low manufacturing experience levels

The students in this study with low manufacturing experience levels, regardless of the manufacturing process, created designs that were more suited for traditional manufacturing than additive manufacturing. A lack of manufacturing experience across both processes forces the students to utilize any design considerations that may be ingrained in their minds, which is most likely traditional manufacturing [35]. Figure 12 shows three designs made by novice students (identifiers ENGE03, IAON06, and UELE03) who identified as having a low traditional manufacturing experience level (1, 2, and 1, respectively) and a low additive manufacturing experience level (2, 2, and 1, respectively).

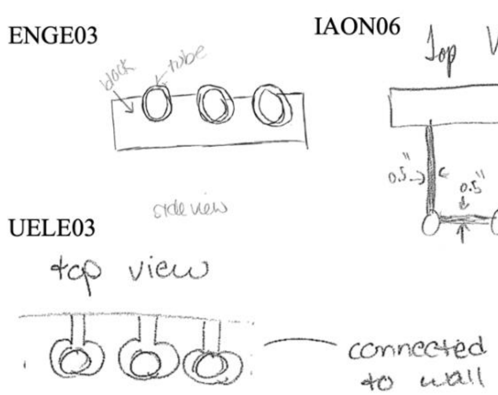


Figure 12. Novice Student Designs

From the raters, these designs received an average traditional manufacturability score of 5.33, 4.67, and 3.67, respectively, an average additive manufacturability score of 2.67, 3.33, and 2.33 respectively, and a ΔCAT score of 2.67, 1.33, and 1.33, respectively. The designs created by the novice students have simple characteristics, such as simple geometries and minimizing the number of parts in the design. For novices, these types of designs are anticipated because they do not yet possess the advanced knowledge to create complex designs. Hence, the common traits found in the designs of novice students are made up of the axioms that define DfTM, as it will be discussed in Section 6.2, increasing manufacturing experience coincides with an increase in design complexity.

6.2 Designs become suited for additive manufacturing only as additive manufacturing experience increases

The hypothesis for this research question stated that increasing the manufacturing experience would increase the manufacturability score. From the results, as the additive manufacturing experience increased, the additive manufacturability score increased as well. As the traditional manufacturing experience increased however, there was not an increase in traditional manufacturability score. Instead, the distribution of scores for additive manufacturability increased. This is a result of the challenges that come from learning new DfM axioms. These challenges appear across all manufacturing experience levels [36].

In contrast to the designs created by the novice students, Figure 13 shows three designs created by expert students (identifiers ENEK04, IUNG06, and ENIA07) who identified as having a high traditional manufacturing experience level (4, 4, and 4, respectively) and a high additive manufacturing experience level (3, 4, and 4, respectively). From the raters, these designs received an average traditional manufacturability score of 2.67, 4.67, and 2.00, respectively, an average additive manufacturability score of 4.67, 2.67, and 4.67, respectively, and a ΔCAT score of -2.00, 2.00, and -2.67, respectively.

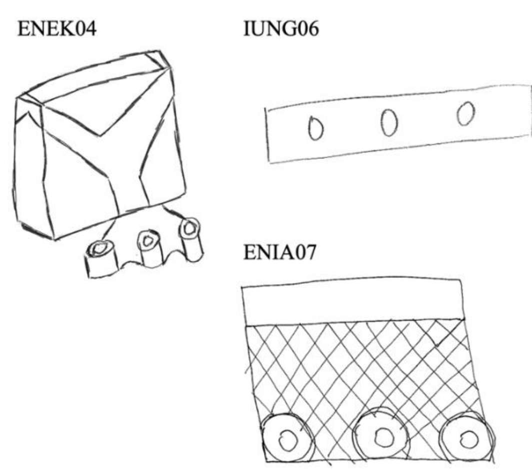


Figure 13. Expert Student Designs

The designs created by the expert students demonstrate far more diversity than the designs created by the novice students. These designs are making use of both sets of DfM axioms, which leads them to be best suited for both manufacturing processes. The design by IUNG06 uses a very simple geometry with ample spacing between the holes, demonstrating that increasing the TM experience level leads to creating designs that are best suited for TM. This aligns with the ΔCAT score distribution shown in Figure 8, where the increased TM experience level led to designs still being best suited for TM. Contrasting this design with the ones made by ENEK04 and ENIA07, they are demonstrating the effects of having extra AM experience. Here, these expert students are incorporating complex geometries while aiming to minimize the amount of material used. These students are making use of DfAM axioms, which leads to the designs being best suited for AM. This aligns with the ΔCAT score distribution shown in Figure 8, where the increased AM experience led to designs becoming more suited for AM. By having expert experience the students are making a subconscious manufacturing choice. Possessing expert experience with the DfM axioms in both manufacturing processes enables the students to pick certain axioms to include in their designs because they have the capability to create a design that is best suited for one manufacturing process over another.

6.3 An increase in manufacturing experience leads to more students self-reporting DfAM axioms

The hypothesis for this research question stated that having a higher experience level with manufacturing will yield more students self-reporting DfM axioms. There was a significant improvement to the self-reported DfAM axioms only. As previously discussed, all students likely have been informally exposed to traditional manufacturing. This informal training means that the students are already familiar with the DfTM axioms, resulting in a lack of a significant difference. Because additive manufacturing is newer, most participants are likely to have not been exposed to the DfAM axioms. The self-reported experience levels, along with the priming content, resulted in significant difference for the self-reported DfAM axioms.

There was one interesting observation made regarding the statistically significant DfAM axioms. One axiom, "*Avoiding Large, Flat Regions*", was statistically significant for traditional manufacturing as well. While no absolute explanation can be given for why this specific axiom stood out compared to the other DfAM axioms, this result justifies the correlated manufacturing experience that was previously discussed. Additionally, this significance may be associated with the specific features that students are incorporating into their designs, which was not addressed in this paper. A future study is needed to investigate the features that students are using when creating designs and whether they are associated with traditional manufacturing, additive manufacturing, or both.

7. CONCLUSION

In this study, an experiment was conducted to observe students' design tendencies based on their previous manufacturing experience. After receiving manufacturing priming content to bring the DfM axioms to the forefront of their minds, they completed a design challenge where the designs were assessed for manufacturability based on expert evaluation and self-assessment. It was found that at low manufacturing experience levels, students' designs are more suited for traditional manufacturing than additive manufacturing. Additionally, informal traditional manufacturing experience meant that only significant changes were observed in the student's self-reported use of DfAM axioms, along with an improved additive manufacturability score based on an increase in the additive manufacturing experience level. These findings are important for the understanding of the students' thought process as they progress through the early-stage design process. For students with low manufacturing experience levels, they are defaulting to using traditional manufacturing axioms based on their informal experience. For students with high manufacturing experience levels, they are making a sub-conscious decision to choose traditional manufacturing or additive manufacturing since they have experience with both processes.

We recognize that by introducing additive manufacturing prior to the design challenge, the concepts will be fresher in their minds compared to the traditional manufacturing concepts presented earlier in the lecture. While some of the students may have exhibited a recency effect [37], this effect was expected to have minimal impact given the small priming content lecture. Furthermore, it has been shown that experience, one of the main variables of study in this paper, does not impact recency bias [38]. Additionally, the small sample size of participants at the lowest and highest levels of experience, while disappointing for data collection, did not have an impact on the significance of the results. In a continuation of this study, the effect of the priming content would become the primary focus of interest. This would be tested by replicating the experiment outlined in this paper while removing the lecture on design for manufacturing. Future studies will investigate the design for manufacturing axioms that students are using in their designs to evaluate what their natural tendencies are, the frequency with which these axioms are used, and the effect of presenting these axioms to students compared to students who do not receive any priming lecture.

ACKNOWLEDGEMENTS

This research was conducted through the support of the National Science Foundation under Grant No. 2042917. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the NSF. We would also like to thank Dr. Randall Bock and Dr. Jason Moore for allowing us to conduct the experiment in their respective classes. Lastly, we would like to thank Jayant Mathur for helping with the statistics calculations.

REFERENCES

[1] Attaran, Mohsen. "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing." Business Horizons 60, no. 5 (2017): 677-688.

[2] Durakovic, Benjamin. "Design for additive manufacturing: Benefits, trends and challenges." *Periodicals of Engineering and Natural Sciences* 6, no. 2 (2018): 179-191.
[3] Prabhu, R., Miller, S. R., Simpson, T. W., & Meisel, N. A. (2020). Teaching Design Freedom: Understanding The Effects Of Variations In Design For Additive Manufacturing Education On Students' Creativity. *Journal of Mechanical Design, Transactions of the ASME*, *142*(9). https://doi.org/10.1115/1.4046065
[4] Prabhu, R., Miller, S. R., Simpson, T. W., & Meisel, N. A. (2020). Exploring The Effects Of Additive Manufacturing Education On Students' Engineering Design Process And Its Outcomes. *Journal of Mechanical Design, Transactions of the ASME*, *142*(4). https://doi.org/10.1115/1.4044324
[5] Yang, Sheng, Thomas Page, and Yaoyao Fiona Zhao. "Understanding the role of additive manufacturing knowledge in stimulating design innovation for novice designers." *Journal of Mechanical Design* 141, no. 2 (2019): 021703.
[6] Starkey, Elizabeth, Christine A. Toh, and Scarlett R. Miller. "Abandoning creativity: The evolution of creative ideas in engineering design course projects." Design Studies 47 (2016): 47-72.
[7] Viswanathan, Vimal K., and Julie S. Linsey. "Design fixation and its mitigation: a study on the role of expertise." *Journal of Mechanical Design* 135, no. 5 (2013): 051008.
[8] Liu, Y-C., Amaresh Chakrabarti, and T. Bligh. "Towards an 'ideal' approach for concept generation." *Design studies* 24, no. 4 (2003): 341-355.
[9] Parnes, Sidney J., and Arnold Meadow. "Effects of" brainstorming" instructions on creative problem solving by trained and untrained subjects." *Journal of educational psychology* 50, no. 4 (1959): 171.
[10] Cross, Nigel. "Expertise in design: an overview." *Design studies* 25, no. 5 (2004): 427-441.
[11] Ahmed, Saeema, Ken M. Wallace, and Lucienne T. Blessing. "Understanding the differences between how novice and experienced designers approach design tasks." *Research in engineering design* 14, no. 1 (2003): 1-11.
[12] Daly, Shanna R., Seda Yilmaz, James L. Christian, Colleen M. Seifert, and Richard Gonzalez. "Design heuristics in engineering concept generation." (2012).
[13] Ratcliff, Roger, and Gail McKoon. "A retrieval theory of priming in memory." *Psychological review* 95, no. 3 (1988): 385.
[14] Tulving, Endel, and Daniel L. Schacter. "Priming and human memory systems." *Science* 247, no. 4940 (1990): 301-306.
[15] Schacter, Daniel L., and Randy L. Buckner. "Priming and the brain." *Neuron* 20, no. 2 (1998): 185-195.
[16] Bonnardel, Nathalie, and Evelyne Marmèche. "Evocation processes by novice and expert designers: Towards stimulating analogical thinking." *Creativity and Innovation Management* 13, no. 3 (2004): 176-186.
[17] Yilmaz, Seda, James L. Christian, Shanna R. Daly, Colleen Seifert, and Rich Gonzalez. "How do design heuristics affects outcomes?." In *DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia*, pp. 1195-1204. 2012.
[18] Lauff, Carlye A., K. Blake Perez, Bradley A. Camburn, and Kristin L. Wood. "Design principle cards: Toolset to support innovations with additive manufacturing." In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 59223, p. V004T05A005. American Society of Mechanical Engineers, 2019.
[19] Laverne, F., Segonds, F., Anwer, N., & le Coq, M. (2015). Assembly Based Methods To Support Product Innovation In Design For Additive Manufacturing: An Exploratory Case Study. *Journal of Mechanical Design, Transactions of the ASME*, *137*(12). https://doi.org/10.1115/1.4031589
[20] Prabhu, R., Leguarda, R. L., Miller, S. R., Simpson, T. W., & Meisel, N. A. (2021). Favoring Complexity: A Mixed Methods Exploration Of Factors That Influence Concept Selection When Designing For Additive Manufacturing. *Journal of Mechanical Design, Transactions of the ASME*, *143*(10). https://doi.org/10.1115/1.4050303
[21] Prabhu, R., Miller, S. R., Simpson, T. W., & Meisel, N. A. (2020). But Will It Build? Assessing Student Engineering Designers' Use Of Design For Additive Manufacturing Considerations In Design Outcomes. *Journal of Mechanical Design, Transactions of the ASME*, *142*(9). https://doi.org/10.1115/1.4046071
[22] Sinha, Swapnil, Hong-En Chen, Nicholas A. Meisel, and Scarlett R. Miller. "Does designing for additive manufacturing help us be more creative? An exploration in engineering design education." In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 58158, p. V003T04A014. American Society of Mechanical Engineers, 2017.
[23] Swamidass, P. M., and G. W. Winch. "Exploratory study of the adoption of manufacturing technology innovations in the USA and the UK." *International Journal of Production Research* 40, no. 12 (2002): 2677-2703.
[24] Prabhu, Rohan, Scarlett R. Miller, Timothy W. Simpson, and Nicholas A. Meisel. "Complex solutions for complex problems? Exploring the role of design task choice on learning, design for additive manufacturing use, and creativity." Journal of Mechanical Design 142, no. 3 (2020): 031121.
[25] Bralla, James G. *Design for manufacturability handbook*. McGraw-Hill Education, 1999.
[26] Prabhu, Rohan, Jennifer Bracken, Clinton B. Armstrong, Kathryn Jablokow, Timothy W. Simpson, and Nicholas A. Meisel. "Additive creativity: investigating the use of design for additive manufacturing to encourage creativity in the engineering design industry." International Journal of Design Creativity and Innovation 8, no. 4 (2020): 198-222.

[27] Williams, Christopher B., and Carolyn Conner Seepersad. "Design for additive manufacturing curriculum: A problem- and project-based approach." In *International solid freeform fabrication symposium*, pp. 81-92. Austin, TX, 2012.
[28] Amabile, Teresa M. "Social psychology of creativity: A consensual assessment technique." Journal of personality and social psychology 43, no. 5 (1982): 997.
[29] Baer, John, and Sharon S. McKool. "Assessing creativity using the consensual assessment technique." In Handbook of research on assessment technologies, methods, and applications in higher education, pp. 65-77. IGI Global, 2009.
[30] Prabhu, Rohan, Jordan Scott Masia, Joseph T. Berthel, Nicholas Alexander Meisel, and Timothy W. Simpson. "Maximizing design potential: investigating the effects of utilizing opportunistic and restrictive design for additive manufacturing in rapid response solutions." Rapid Prototyping Journal (2021).
[31] Bartko, John J. "The intraclass correlation coefficient as a measure of reliability." Psychological reports 19, no. 1 (1966): 3-11.
[32] Weir, Joseph P. "Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM." The Journal of Strength & Conditioning Research 19, no. 1 (2005): 231-240.
[33] Fleiss, Joseph L., and Jacob Cohen. "The equivalence of weighted kappa and the intraclass correlation coefficient as measures of reliability." Educational and psychological measurement 33, no. 3 (1973): 613-619.
[34] Lee, James, David Koh, and C. N. Ong. "Statistical evaluation of agreement between two methods for measuring a quantitative variable." Computers in biology and medicine 19, no. 1 (1989): 61-70.
[35] Blösch-Paidosh, Alexandra, and Kristina Shea. "Design heuristics for additive manufacturing validated through a user study." Journal of Mechanical Design 141, no. 4 (2019).
[36] Dinar, Mahmoud, and David W. Rosen. "A design for additive manufacturing ontology." Journal of Computing and Information Science in Engineering 17, no. 2 (2017).
[37] Mingay, David J., and Michael T. Greenwell. "Memory bias and response-order effects." Journal of Official Statistics 5, no. 3 (1989): 253-263.
[38] Arnold, Vicky, Philip A. Collier, Stewart A. Leech, and Steve G. Sutton. "The effect of experience and complexity on order and recency bias in decision making by professional accountants." Accounting & Finance 40, no. 2 (2000): 109-134.