EXAMINING THE EFFECT OF DESIGN FOR ADDITIVE MANUFACTURING RULE PRESENTATION ON PART REDESIGN QUALITY

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Richard Nwaeri

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EXAMINING THE EFFECT OF DESIGN FOR ADDITIVE MANUFACTURING RULE PRESENTATION ON PART REDESIGN QUALITY

Approved by:

Dr. Katherine Fu, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. David Rosen
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Julie Linsey
School of Mechanical Engineering
Georgia Institute of Technology

Date Approved:
April 8th, 2019

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SUMMARY

The main goal of this thesis is to the study the way design for additive manufacturing (DfAM) rule presentation affects a designer's ability to utilize those rules. To that end a pair of studies were carried out. The first study was conducted with industry engineers and designers, while the second study was conducted with students at a university. For both studies, four DfAM design rules for fused deposition modeling (FDM) were chosen, relating to overhangs, planar surfaces, accessible support structures, and part size. Each rule was presented in four different modalities: text only, text with illustration, text with industry example, and text with 3D printed example. Each rule presentation included a justification, and all but the text-only presentation included a "desirable" and "undesirable" design example for the rule. Four-part redesign problems were given, and their pairing with presentation type and order were randomized. The resulting redesigns were then rated on both novelty and quality. Results indicate that although there are no differences in quality and novelty scores between modalities, the text only rules were perceived to be the most difficult to understand. Furthermore, a comparison between the professionals and the students showed that the professionals created higher novelty redesigns. These results have several implications in the field of DfAM education.

CHAPTER 1: INTRODUCTION

Motivations

Additive manufacturing, or 3D printing as it is more commonly known, refers to a class of manufacturing processes which all revolve around the idea of creating a 3D object one layer at a time by stacking these layers on top of one another. These differ from traditional subtractive manufacturing processes in that, rather taking a large piece of material and removing material in order to create a finished part, small pieces of material are added together to create the part, hence the name additive manufacturing. While these processes are not necessarily new, in recent years, their popularity has skyrocketed due to the increase in both the affordability of the machines as well as the advancements in additive manufacturing technology. Given the numerous differences between additive and subtractive processes, it has become increasingly important to ensure that designers understand the technology and its unique limitations. For this reason, the field of design for additive manufacturing (DfAM) has emerged, which is focused on the ways designers can best adapt their parts to make use of the opportunities additive manufacturing technology presents.

In order to facilitate the spread of DfAM understanding, several avenues have been explored in addition to the traditional classroom experience, such as virtual classrooms and workplaces, which replicate the interface of the machines in order to familiarize designers with the processes in a low-risk environment. One problem, however, is that in the case of additive manufacturing, there is a unique issue which can be seen. Rather than education being primarily an academic problem which concerns teachers and professors, it is a problem which primarily concerns workers in industry, as the process has grown too quickly for current industry professionals to be well acquainted with it. As a result, the education process needs to be as quick and practical as possible so they can quickly adjust designs as needed, as opposed to the more rigorous explanations typically given in classrooms. Heuristics are typically well suited to this as they allow large amounts of information to be condensed into a set of key points. This can be particularly useful for computerized tools, such as CAD extensions, for which brevity is a requirement.

Regardless of the method used for instruction, one important question is how best to display this information, and this question lies at the heart of this thesis. Building upon the work done by Dinar and Rosen [1], which focused on the formalization of DfAM guidelines, this thesis seeks to better understand the differences between the different modalities of presentation of DfAM rules, and ultimately make recommendations about which presentations are the most beneficial for aiding designers in making their parts suitable for additive manufacturing. Furthermore, given the importance of instructing both students and professionals, comparisons will be made between expert and novice instruction to determine whether any considerations need to be made when transferring an instruction method from one context to the other.

Research Questions

Based on the goals stated above, there are 2 major research questions that are addressed by this thesis:

1. How does modality of design rule presentation affect quality and novelty of DfAM redesign?

2. How do these effects vary with design expertise?

The first question is important, as there need to be metrics to assess the effect of different modalities on the performance of the designers. If certain modalities yield higher quality scores, it would indicate that those modalities lead to redesigns that are more appropriate for additive manufacturing; this would be desirable, as it indicates those modalities are straightforward to understand. Similarly, if certain modalities lead to higher novelty scores, it indicates that they are better at stimulating the production of novel redesigns; this is important, as oftentimes the most ideal redesign is not particularly intuitive, and so modalities that are able to invoke these novel redesigns may be preferred. The second question is important because it allows the results to be generalized to the two key groups for which it could be useful.

Organization of Thesis

This thesis is divided into 6 chapters (including this one), each with multiple subsections. Chapter 2 gives a review of the various fields connected to the main subject of this thesis, which include, design for additive manufacturing, heuristics, presentation modality and expert-novice differences. Chapter 3 summarizes the various tools and metrics created to conduct the study, as well as the way the data collection was carried out. It also briefly covers the rationale behind decisions made at several points throughout the creation of the experimental design. Chapter 4 presents the demographic information and results of the data analysis. It also includes a description of the statistical tests used to generate these results, and an explanation as to why each test was used. In Chapter 5, the interesting findings from the results, as well as their implications, are discussed in detail. This then leads into a description of the contributions this thesis adds to various fields. To finish the chapter, a detailed discussion at the limitations of this study is provided, along with some suggestions for how future studies can be improved. Finally, Chapter 6 includes a summary of the conclusions that can be drawn from this thesis.

CHAPTER 2: LITERATURE REVIEW

Design for Additive Manufacturing

In recent years, an increasing number of designers have realized the benefits of concurrent engineering [2]. This refers to a system in which the different disciplinary groups working on different phases of a product work closely together to ensure that all facets of the product are considered at every phase of product development. This is done in order to improve the likelihood of a successful product, while also reducing costs and enabling flexibility along the way. This has spawned an approach to design known as Design for X (DfX), which is an umbrella term for a group of more focused approaches which aim to help designers consider the later stages of the product, while still in the design phase. One of the most common of the approaches is Design for Manufacture and Assembly (DfMA), which is focused on helping designers create concepts that are easier to manufacture, helping to reduce costs further down the road. This is done by introducing them to the key features that should be considered in order to reduce manufacturing complexity, such as the expected assembly directions, and the number of fasteners [3].

Given the unique nature of additive manufacturing, it stands to reason that it requires a completely new set of considerations when designing with the intention of using it as the primary method of manufacturing [4, 5]. For example, while typical manufacturing methods must focus on reducing part complexity as much as possible in order to reduce both tooling costs and production times, additive manufacturing processes don't have this restriction, as the cost is generally unaffected by the complexity of the design [6]. Conversely, factors such as part orientation [7] and support material optimization [8] are considerations completely unique to additive manufacturing, which can be devastating if ignored. These two types of considerations represent the two main aspects of design for additive manufacturing (DfAM) and have been referred to as opportunistic and restrictive DfAM, respectively [9].

Opportunistic DfAM refers to any DfAM method that aims to utilize the unique advantages that DfAM provides over traditional manufacturing methods. While this generally refers to taking advantage of the geometric freedom offered by additive manufacturing, given the increasing use of multi-material AM processes, there have also been several methods taking advantage of this freedom of material choice/properties, as well [10]. One of the best examples of these opportunistic DfAM methods is topology optimization, in which the material in a part is redistributed to optimize certain user-defined design parameters while still fulfilling all the requirements of the original part. This process has yet to be perfectly adjusted for additive manufacturing techniques [11], as there is still much work to be done before it fully captures all of the aspects of a 3D printed part; for example, a lack of consideration for build orientation and part distortion makes topology optimization a purer representation of opportunistic DfAM, as those considerations generally fall under restrictive DfAM.

In contrast to opportunistic DfAM, restrictive DfAM refers to the considerations that must be made when using additive manufacturing that simply don't exist when using traditional manufacturing methods. While the specifics of restrictive DfAM can generally vary greatly between processes, materials, and even between individual machines, there are a few considerations that are more or less universal. One of the most notable of these is build orientation, as additive manufacturing processes generally employ a layer-by-layer approach, meaning the structural properties of the final part can vary greatly depending on the way the part is oriented. Several processes may also require additional support structures if printed in certain ways. These are generally undesirable, as they increase material cost and can have negative impacts on both surface finish and post-processing time. For the purpose of this thesis, DfAM will generally be thought of in the restrictive sense, primarily because the design changes that restrictive DfAM requires are inherently narrower in scope compared to the more fundamental changes that opportunistic DfAM inspires.

In terms of the implementation of either type of consideration, ideally designers would be adopting a “global approach” to additive manufacturing [12], in which they decide on using additive manufacturing before they begin the design process. This has been shown to be quite effective, as it allows designers to take full advantage of the opportunities that additive manufacturing presents, rather than simply building upon parts made for other processes. However, given the rapid growth of the additive manufacturing industry [13], there has been little time for current industry professionals to properly familiarize themselves with the process, making this approach difficult to apply in practice. One solution to get around this has been to computerize the process by utilizing optimization techniques to create CAD tools that could potentially improve designs [8, 14]; while some of these techniques show a lot of promise, they are still far from widespread, and will take significant time to become standard in industry. Until the industry reaches a point where either approach to design for additive manufacturing becomes feasible, a simple method to aid designers in transforming their design into AM-ready parts is necessary, and this is where heuristics come into play.

Heuristics

Heuristics are often colloquially referred to as guidelines or rules-of-thumb. Fu et al. [15] performed an in-depth review on the literature surrounding design heuristics in an effort to determine the key characteristics of a heuristic. Based on these characteristics, one way to describe a heuristic is as a context-action pair, which provides an adequate solution to a problem with minimal search time. It is important to note that heuristics are not intended to provide optimal solutions, but merely provide satisfactory solutions given a specific context.

In the realm of additive manufacturing, the specific context is particularly important. This is because, when compared to traditional manufacturing processes, the necessary process parameters vary much more, as they depend on the material, the AM process used, and the specific machine being used [16]. As a result, much of the research into DfAM heuristics has focused on specific processes or machines [17, 18]. This is not to say that there are no general guidelines for additive manufacturing as a whole, as research has certainly been done into generating process independent guidelines. Blösch-Paidosh and Shea [16] created a list of 29 general heuristics based on their analysis of hundreds of existing AM designs. Similarly, Adam and Zimmer [19] found several heuristics that are applicable to multiple processes when deriving heuristics for Laser Melting, Laser Sintering and Fused Deposition Modeling individually. While general heuristics like these may lack the specificity needed to acquire near optimal designs, they make up for it with their wide applicability.

While there are potentially valid concerns about the use of heuristics given that they often provide sub-optimal solutions, it is important to note that truly optimal solutions are very rarely ever required, particularly in the field of design, and often are simply unachievable [20]. As a result, despite these concerns, research has continued looking into the potential benefits heuristic use provides. Yilmaz et al. [21] showed that the application of design heuristics aided designers in the creation of more novel designs. Similarly, in the field of DfAM, Blösch-Paidosh and Shea [22] showed that by exposing novice designers to the general DfAM heuristics they previously generated [16], they were able to improve the designers' ability to redesign for additive manufacturing. Given the evident benefits that heuristic use provides for design for additive manufacturing, one of the key next steps is to study the way these heuristics are presented to designers.

Presentation Modality

The modality effect refers to the theory that presenting the same information through multiple modalities can improve retention of information and understanding. While the exact explanation behind this effect is often a topic of debate in psychology literature [23], one common explanation is based on the Cognitive Load Theory proposed by Sweller et al. [24]; this theory suggests that by utilizing multiple modalities to present information, the strain on any one system is reduced, thereby improving one's ability to learn. While this effect is typically used to explain the importance of utilizing both visual and auditory representations for learning [25], specific visual modalities have also been studied such as animations and non-verbal gestures [26]. Most studies done in this area of psychology have found the modality effect to be significant in several different experimental setups, which has warranted further research to understand its impact on design.

In the field of design, research on the effect of modality has primarily been focused on example modality for analogical design. Analogy in the context of design refers to the transfer of knowledge from another field or the use of ideas from a functionally similar product in order to facilitate the design and development of a new product [27]. This emphasis of example modality in analogical design largely stems from the fact that if analogies are to be actively used in aiding the design process, as many have suggested [28], the ideal way to communicate these analogies should be found [29]. Congruently, given the benefits that providing heuristics has on the design process, the ideal way to communicate these heuristics must also be found.

Several studies have already been performed in the field of design with this idea in mind. Chan et al. [29] showed that participants exposed to text based examples produced a lower number of ideas and also tended to borrow more from the examples than those who were exposed to pictorial examples. Toh and Miller [30] found that exposing participants to a physical example led to reduced novelty and variety of solutions when compared to a pictorial example, suggesting that physical examples may be detrimental to early stage design. Viswanathan and Linsey [31] studied this design fixation effect more in depth and found that even when de-fixation techniques were used, physical example groups still tended to replicate the example solutions more than the pictorial example groups. However, they also generated more non-redundant ideas, suggesting the effects of modality on design fixation are not as clear as they may appear. Barnawal et al. [32] studied design for manufacture specifically and found that by varying the modality in which designers were given feedback for redesigns (none, text, 2D views, 3D CAD model), their performance could be affected in several ways. Specifically, the 2D and 3D modality groups showed higher performance and confidence in their designs than the other groups. Furthermore, subjects in the 3D group rated the feedback as all round more useable than the other groups, indicating subjective preference for the 3D representation.

Despite the abundance of work on modality within design, there are still a few gaps that this work fills. First, in most if not all studies, the designers are given very open-ended design problems, so the effect of presentation modality in cases where the design space is restricted has yet to be observed. Furthermore, additive manufacturing is somewhat unique in that a variety of manufactured parts can be made with ease and used as instructional material. This introduces a new modality for comparison that has yet to be explored, particularly in the context of heuristics. While similar hands-on approaches have been applied to other studies, this is unique in that rather than attempting to show how a product works using a physical example, the workings of a process are being explained through the use of an example, which changes the way designers need to understand it to make use of it. Finally, very few studies of this type have explored the effects of the participant's level of expertise as a moderating variable; this could be an important factor, as novice designers have been shown to differ in many ways from experts, which will be discussed next.

Experts vs Novices

As one of the primary applications of this work is in the field of education and workforce development, it is just as important to examine the learner/trainee as it is to examine the content being taught. One of the most notable potential differences that can be seen in designers attempting to understand design for additive manufacturing is their level of expertise in design generally. It should be noted that the terms expert and novice are used quite liberally here, as although some efforts have been made to create more formal classifications of different levels of expertise [33], descriptions of experts and novices vary greatly within the literature. Regardless of the precise thresholds between experts and novices, in a general sense, expertise can be thought of as a wealth of domain-specific knowledge (or ability), acquired from a long period of sustained practice [34].

While the general concept of an expert is not new, the behavior of experts in design differs from that of experts in other fields in a few notable ways. For example in a review of design expertise literature, Cross [34] observed that design experts tend to begin a design problem by very quickly generating initial solutions, rather than attempting to fully define the problem first. This suggests a solution-focused approach, as opposed to a problem-focused one (or at least an approach that looks at both in tandem). Furthermore, Cross also observed that many expert designers tend to focus on iterating upon a single solution concept, rather than creating a wide range of alternatives, as would typically be expected of an expert. Unique differences such as these make design expertise a particularly worthwhile area to study in order to better understand the reasons behind these differences.

While much of the work on expertise in design has focused on fairly open-ended problems, there have been a few studies focused on the way expertise affects the solutions to more constrained problems, such as the redesign tasks that are assessed in this work. These redesign tasks differ from typical design tasks in that rather than make a new design from scratch, participants must start with a base concept and adjust it as necessary, which naturally limits the design space they can reasonably explore. One such study done by Crismond [35] examined the effect expertise has on the solution strategies of pairs of participants redesigning simple mechanical devices. The results indicated that experts were better at connecting scientific concepts to their design and used more rules of thumb than their novice counterparts. The work presented in this thesis is unique in that it is looking at how one's expertise in design and design for traditional manufacturing affects one's ability to learn to design for additive manufacturing. Examining the effect of one's expertise in a closely related area is a niche that has yet to be explored in this context.

Conclusions from Literature: Hypotheses

Based on this literature review, there are a few hypotheses that can be made about the expected answers to the research questions posed above. With regard to the first question, as physical parts have been shown to run the risk of leading to design fixation [31], it is believed that the **participants exposed to the printed parts will have the lowest novelty scores (H1a)**. **Participants exposed to text-based rules are expected to have similarly low scores for novelty (H1b)** [29]. On the other hand, in terms of quality, the effect of a printed part is unknown, however it is believed that the **text-based rules will lead to the lowest quality scores (H1c)**, based on prior work [32]. Finally, it was found that there was **subjective preference of the 3D modality** [32], over 2D and text modalities, so it is believed that similar results will be seen here **(H1d)**.

For the second question there are two major hypotheses. First, with regards to novelty, it is believed that **experts will have on average, higher novelty scores (H2a)**, as they have a wider range of experiences to potentially draw inspiration from [34]. For similar reasons, it is believed that **experts will also exhibit higher quality scores (H2b)**. Although that said, it should be noted that given the many differences between designing for additive manufacturing and traditional manufacturing, it is possible that the experts' experience in traditional manufacturing may actually negatively impact their ability to apply these DfAM rules. This is primarily speculation however, as it has yet to be seen if this is a concern.

CHAPTER 3: METHODOLOGY

Developing the Study

The purpose of this work is to understand how design rule presentation can affect redesign quality and novelty. Development of the research study began by identifying applicable DfAM rules of thumb, design problems, and modes of presentation. The design rules and correlating problems chosen for this study are shown in Table 1. These rules were selected from a larger set of DfAM rules [18] based on how suitable they were to be applied to a design problem that could be completed within the anticipated time (roughly 10 minutes). Designs chosen were simple enough to be shown in one drawing, but complex enough for multiple redesign solutions to exist. Each rule was associated with only one design problem, and every design problem consisted of at least one flaw that could be improved by using the correlated design rule. For example, the “Juicer” problem contains overhangs that will require support material during manufacturing. Every participant was asked to apply the “overhangs” design rule to redesign the juicer, but it is not expected to be applied to any other design.

Table 1: Design rules chosen for study

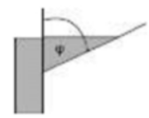
Rule	Description	Problem
Overhangs	If there is an overhang on the part, ensure that the angle is smaller than 40°.	Juicer
Planar Surfaces, Prismatic Joints	If mating surfaces are large, add holes or pockets to one to reduce contact area.	Pencil Case
Accessible Support Structures	If your part requires support structures, make sure they are not trapped inside an inaccessible volume.	Soap Dish
Part Size	If the part is larger than the build area in one dimension, either reorient it, or split the part into two.	Paper Towel Holder

After identifying design rules and problems, four different modes of presentation were chosen:

Text Only: Rules were presented using the description shown in Table 1 along with a justification for why each rule makes a design better suited for additive manufacturing.

Rule	Justification
If there is an overhang on the part, ensure that the angle is smaller than 40°	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than 1mm. As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.

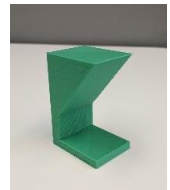
Text with Illustration: The same description and justification from “Text Only” were presented along with 2D illustrations. One illustration shows an unfavorable design when the rule is ignored, and the second illustration shows a favorable design when the rule is applied.

Rule	**Justification**	**Favorable**	**Unfavorable**
If there is an overhang on the part, ensure that the angle is smaller than 40°	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than 1mm. As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.		

Text with Industry Example: Similar to “Text with Illustration”, this presentation contains the rule description, justification, and favorable/unfavorable designs. However, this mode of presentation uses 3D examples of real products such as a bolt/lock, cup, and speaker.

Rule	**Justification**	**Favorable**	**Unfavorable**
If there is an overhang on the part, ensure that the angle is smaller than 40°	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than 1mm. As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.		

Text with Printed Part: This mode of presentation also contains a description, justification, and favorable/unfavorable designs. The designs are presented as 3D-printed parts that the participant can physically hold and analyze.

Rule	Justification	Favorable	Unfavorable
If there is an overhang on the part, ensure that the angle is smaller than 40°	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than 1mm. As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.		

Each rule as presented in all four modalities can be found in Appendix A. Each associated design problem can be found in Appendix B. Each design rule, associated design problem, and mode of presentation occurs only once per participant. A two-level randomization process was used to assemble experimental packets. Randomization was performed using an online random number generator. The first level randomized the order in which each design rule is presented to the participant. The second level randomized the mode of presentation of the design rule. An example experiment packet is shown in Table 2. Design problems were placed in individual envelopes labeled Phase A-D so participants did not attempt problems out of order and were only looking at one problem at a time.

Table 2: Example Study Packet Layout

Phase	Rule	Problem	Presentation
A	Accessible Support Structures	Soap Dish	Text with 3D-Printed Part
B	Part Size	Paper Towel Holder	Text Only
C	Overhangs	Juicer	Text with Industry Example
D	Planar Surfaces	Pencil Case	Text with Illustration

Study Procedure

There were two groups of participants recruited for this study. The first set of participants chosen for the study was comprised of engineers taking part in a DfAM short course at Siemens in Orlando, FL. The purpose of the DfAM short course was to introduce participants who were unfamiliar with additive manufacturing to the considerations needed for DfAM, as well as the underlying principles behind several additive manufacturing processes. It then went into several more detailed additive manufacturing principles, which are outside the scope of this project. The full outline can be seen in Appendix C. At the end of the one-day of the short course, the research team introduced the study to workshop participants. Experiment packets were passed out containing consent forms, and those who agreed to volunteer signed the consent forms and remained in the conference room. Those who did not consent to the study were allowed to leave. Twenty-seven participants in total agreed to take part in the study. No compensation was given to those who decided to participate. This first set of participants is intended to represent the expert group, as although they are mostly new to additive manufacturing, they have a lot of experience with design and manufacturing as a whole.

The second set of participants chosen for the study was made up of undergraduate students from an introductory engineering design class at a university. In place of a workshop, the students were given 2 1-hour lectures on design for additive manufacturing during their regular lecture periods prior to taking part in the study. The material shown during these lectures went into less detail than the short course; however, a similar amount of time was spent on the key information that was most directly related to the design problems. The lecture slides can be found in Appendix D. Similar to the expert group, the students were given consent forms during the class the study was to be performed in; although unlike the expert group, class credit was offered as compensation for taking part in the study. 56 students agreed to take part in the study, and an alternate assignment was provided for students who did not consent. This second set of participants is intended to represent the novice group, and were selected to contrast with the expert group, as the students are unfamiliar with design, additive manufacturing and traditional manufacturing.

In both groups, after introducing the study and obtaining consent, one researcher used a script to navigate participants through the remainder of the study. Participants were prompted to take the Phase A envelope from the experiment packet. Ten minutes were allotted to read the given materials and complete the redesign task. These study instructions can be seen in Appendix E. Researchers alerted participants when there were 5 minutes and 1-minute remaining. After the ten minutes were completed, Phase A materials were placed back into the packet before retrieving Phase B. This was done to ensure participants did not return to previous problems or begin future problems outside of the allotted ten minutes. This process was repeated for Phases B-D. After Phase D, participants took 5-10 minutes to complete the provided survey. A copy of this survey can be found in Appendix F. Then, all materials were returned to the packets, and the packets were collected by the researchers.

Assessing Quality and Novelty

After data collection, two researchers developed coding schemes for quality and novelty of the design solutions. The decision to focus on quality and novelty as the criteria for the metrics was based on the framework created by Shah et. al [36]; although, the specifics of both metrics were created specifically for this study. No other metrics were used, as each participant only produced one solution per problem, making other metrics such as variety and quantity unsuitable. For quality, five criteria were used to judge a design's ability to carry out all original functions while improving the quality of the part design for additive manufacturing.

Functionality: Two main functions were determined for each design presented to the participants. A positive score was given to participants who maintained both functions in the redesign. Neutral scores were given if only one function was maintained, and negative scores were given if neither function was maintained in the solution.

Design Material: It was determined that a design is of higher quality if it carries out the same functions using less material. Therefore, solutions using less material than the original design were given positive quality scores. Solutions using the same amount of material were given neutral scores, and those implementing more material were given negative scores.

Support Material: It was determined that a design is of higher quality if it requires less support material during manufacturing, as this reduces the total amount of material needed for production. Solutions using less support material than the original design received positive scores, those with the same amount of support material received neutral scores, and those that required more support material received negative scores.

Number of Parts: It was determined that a design requiring more parts would be of lower quality than a design requiring less parts. This is due to the imperfections that can arise when printing, as well as the additional connections and maintenance required to ensure the additional parts maintain the same structural soundness as a full piece. Solutions using the minimum number of parts necessary to print while maintaining functionality were given positive scores, and scores were reduced as additional parts were added to the system.

Strength of Print: The print orientation designated could lead to weaker or stronger designs depending on the way forces will act upon the design during its use. The most likely forces applied to each design were identified. From these forces, it was decided which orientations would lead to stronger or weaker designs. It was ultimately decided that in general horizontal print orientations that had their layers run perpendicular to the likely direction of force would make each design strongest and would receive positive scores. Vertical print orientations which had their layers run parallel to the likely direction of force made designs weakest and received negatives scores. Any diagonally oriented designs were given neutral scores. If the participant did not indicate a print orientation, it was assumed that the print orientation did not change from the original.

Two researchers independently examined and rated the quality of 25% of the participants. Inter-rater agreement was calculated for 25% of the solutions in order to ensure that if Cohen's kappa was too low, inter-rater agreement could be carried out again with a new set of participants once the rubric had been altered. Both raters were engineering design graduate students who were familiar with the project as well as the metrics used. Inter-rater agreement across all quality criteria resulted in 90% agreement and a sufficient Cohen's kappa of 0.84. This Cohen's kappa was acquired by analyzing each sub-category score in the same analysis. One researcher then coded the remaining participants. A final quality score was calculated using a weighted sum of the individual scores. Functionality was given a weight of 0.5, while the other 4 categories were given a weight of 0.125 each. This was done because regardless of how suitable a part is for 3D printing, if it is unable to be used for its intended functions, it can't be considered a good design; thus, it is reasonable for the functionality to be weighted the same as all other categories combined. Sample redesigns along with their quality scores can be found in Appendix G

The first 25% of participant data was studied again by two researchers to develop an initial set of novelty categories. Four categories for each design problem were identified where solutions seemed to vary the most. For example, soap box solutions primarily differed through modifications to the main architecture, mid-plate design, support type, and print orientation. Researchers then independently identified if/how original designs were modified within each category. This was done with 93.75% agreement and a sufficient Cohen's kappa of 0.77. One researcher then coded the remaining data for novelty. Novelty scores for individual categories were based on how few designs fell into that category, such that a design that was the only member of its sub-category scored a 1, while if all designs fell into the same sub-category, they would all receive a score of 0 in that category. The overall scores were then acquired by simply summing the individual category scores, then normalizing the scores to a score out of 1. This novelty calculation is based on the method suggested by Shah et. al [36].

CHAPTER 4: RESULTS

Demographics: Experts

The expert study initially consisted of twenty-seven male participants, however one was excluded due to failure to sign the consent form. Of the remaining 26 participants, 3 were aged 27-30, 11 were aged 31-40, 5 aged 41-50, 4 aged 51-60, 3 aged 61-70 and 1 did not say (Figure 1). Ten participants identified as Asian / Pacific Islander, 12 as Caucasian, 1 as Latino, and 3 other/did not say (Figure 2). Participants averaged 9.8 ± 7.3 years at their current company, 9.8 ± 9.7 years design experience, and 15 ± 10.4 years engineering experience. Six participants had a bachelor's degree as their highest degree earned, 11 had master's degrees, 8 had a PhD, and 1 had a vocational certificate (Figure 3). Twenty participants had a background in mechanical engineering, 2 in material science, 4 in aerospace engineering, and 6 in other fields. 23 participants worked as some form of engineer at the company. In terms of their prior experience with additive manufacturing, on a scale of 1-5 with 5 representing 'Very Experienced' and 1 representing 'Completely Inexperienced', 4 participants rated themselves 4, 2 participants rated themselves 3, 7 participants rated themselves 2, while 13 rated themselves 1 (Figure 6).

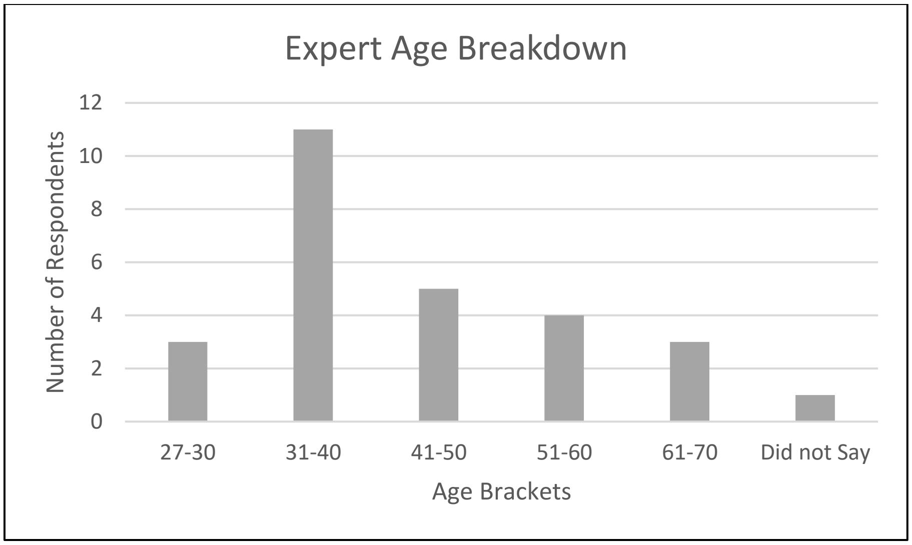


Figure 1: Age Distribution within Expert Study

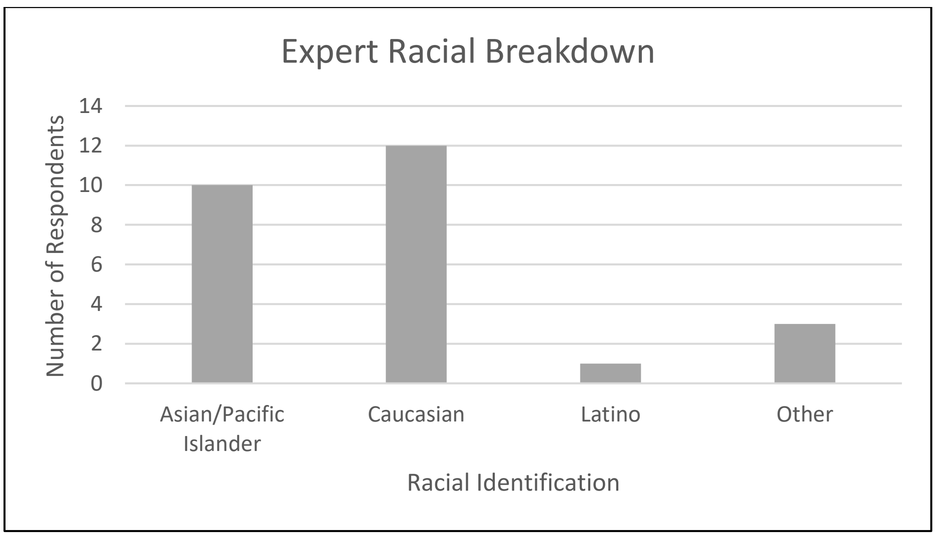


Figure 2: Racial Distribution within of Expert Study

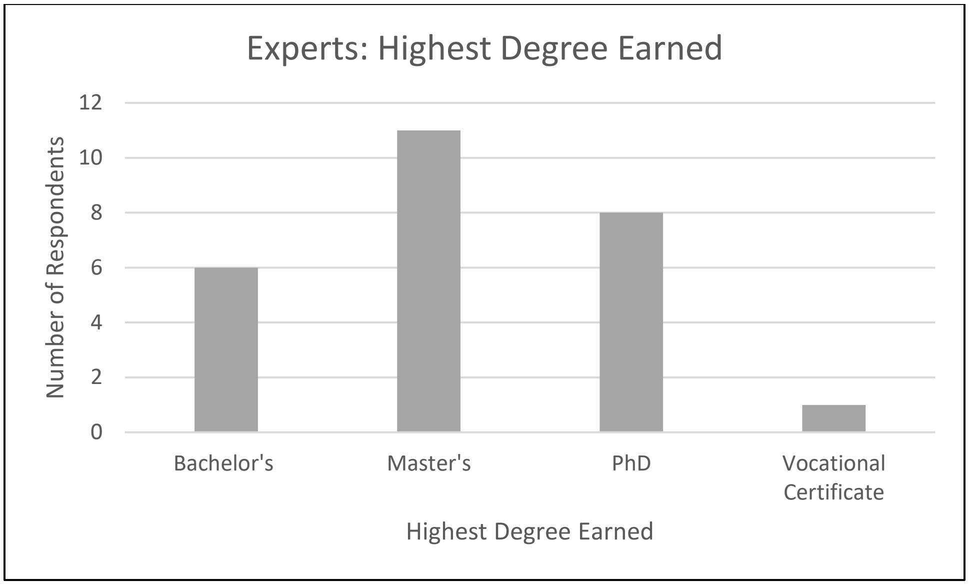


Figure 3: Distribution of Highest degree Earned within Expert Study

Demographics: Novices

The novice study consisted of 56 participants, of which 22 were female and 34 were male. No participants were excluded from the novice study. Of the 56 participants, 48 were aged 18-20, 7 were aged 21-23 and 1 was aged 24-26 (Figure 4). One participant identified as Arab, 13 identified as Asian / Pacific Islander, 33 identified as Caucasian, 5 identified as Hispanic, 4 identified as Latino, 4 identified as multiracial and 1 identified as ‘other’ (Figure 5). As the novice study consisted of students who were assumed to have no significant design or engineering experience outside of school, this data was not collected from the novices. However, when asked to rate their prior experience with additive manufacturing, on a scale of 1-5 with 5 representing ‘Very Experienced’ and 1 representing ‘Completely Inexperienced’, 1 participant rated him/herself 5, 3 participants rated themselves 4, 6 participants rated themselves 3, 16 participants rated themselves 2, while 30 rated themselves 1 (Figure 6).

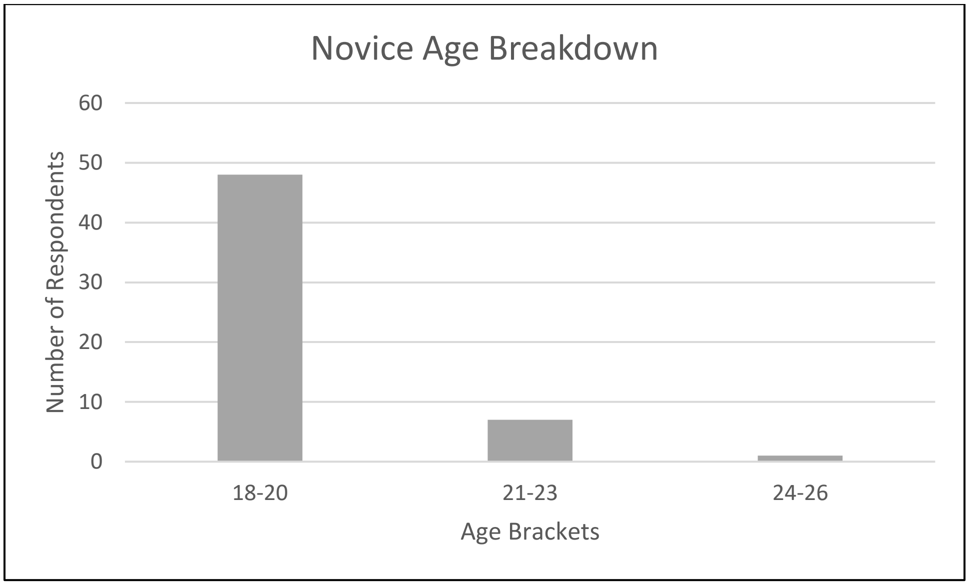


Figure 4: Age Distribution within Novice Study

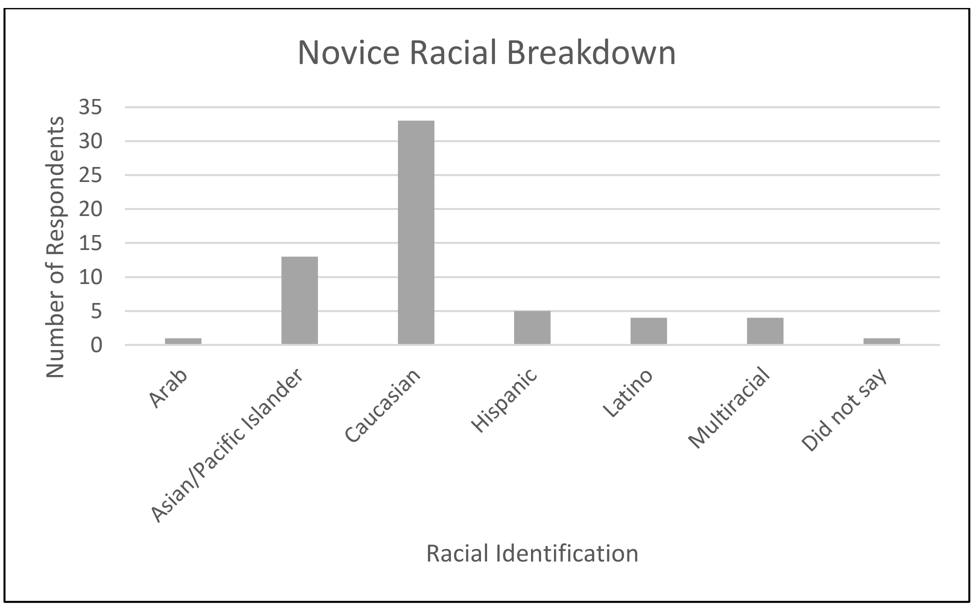


Figure 5: Racial Distribution within Novice Study

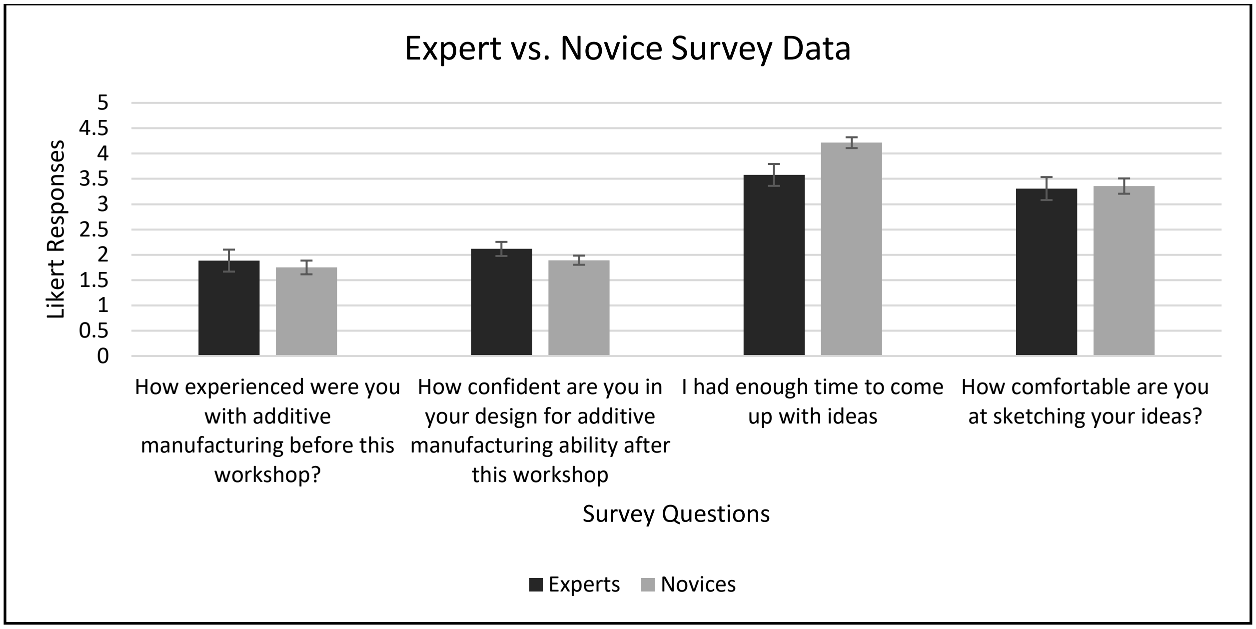


Figure 6: Survey Responses of Experts and Novices. Error bars show ±1 SD

Data Analysis

To analyze the effect of the rule presentation on quality and novelty, a repeated measures ANOVA was used for the expert data. In the novice data however, a linear mixed model was used in order to account for repeated measures while still utilizing as much data as possible. This was necessary because the paper towel problem was ultimately excluded from the novice data analysis due to an error in the problem presented to the novices. Regardless of the analysis used, any problem in which the subject indicated they did not know how to solve the problem was given a score of -1 for quality and 0 for novelty, the lowest score possible in either case.

To analyze the effect of the rule presentation on rated ease of understanding, the non-parametric Kruskal-Wallis test was used. For cases in which the overall effect was found to be significant, the Student-Newman-Keuls test was additionally run to check for significant pairwise differences. A similar approach was used to analyze the other Likert-scale survey responses.

To test the effects of expertise on quality and novelty, a linear mixed model was used in order to account for both repeated measures and the rule presentation modality. It should be noted that for these analyses, the paper towel problem was also removed from the expert's data in order to ensure the expert and novice data sets were comparable. To assess the effects of expertise on ease of understanding and the other Likert-scale survey responses, the non-parametric Mann-Whitney U test was used. All analysis was done at a 95% confidence level unless otherwise stated. The direct SPSS output for all tests can be found in Appendix H.

Analysis Results

Based on the aforementioned tests, it was found that the quality of the redesigns was not significantly impacted by rule presentation modality (Figure 7) for both experts and novices ($F(3,75)=0.922$, $p=0.435$ and $F(3,39.2)=1.082$, $p=0.368$ respectively). Similarly, the novelty of the redesigns was also non-significantly impacted by the rule presentation modality (Figure 8) for both experts and novices ($F(3,75)=0.639$, $p=0.592$ and $F(3,41.1)=0.007$, $p=0.999$ respectively).

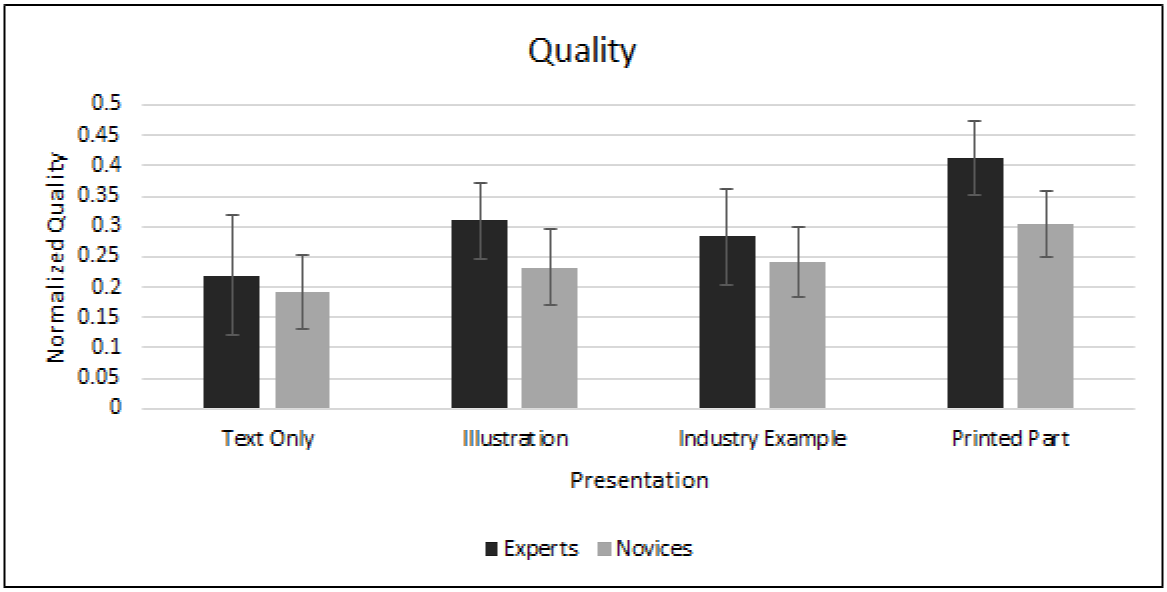


Figure 7: Quality of Redesign Solutions of Experts and Novices. Error bars show ±1 SD

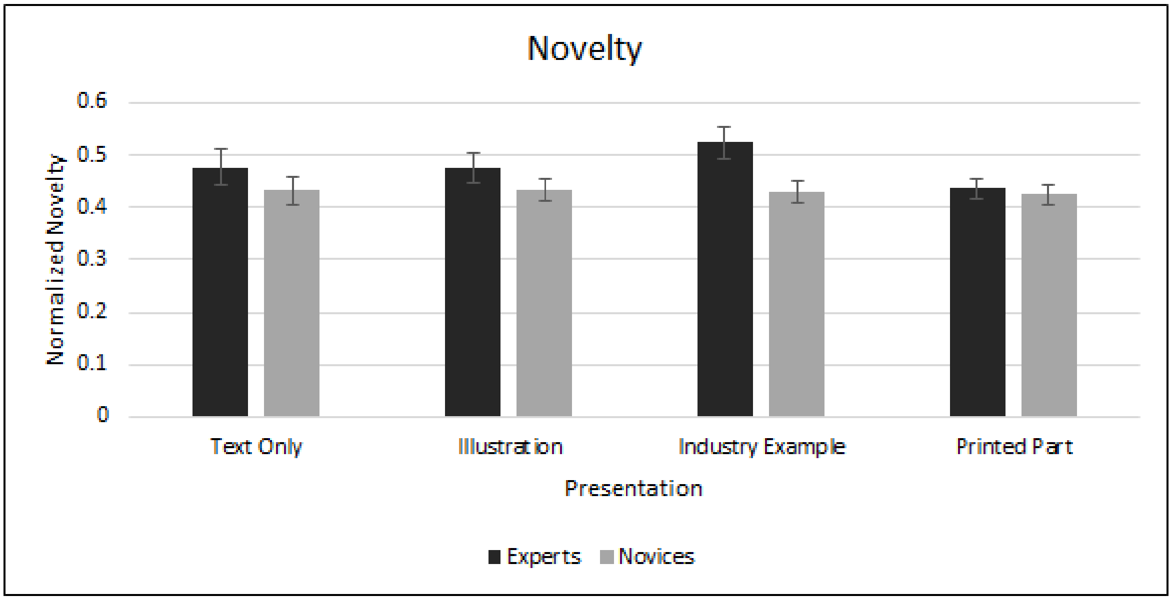


Figure 8: Novelty of Redesign Solutions of Experts and Novices. Error bars show ±1 SD

The analysis of the effect of rule presentation modality on rated ease of understanding showed there was a significant effect of presentation (Figure 9) for both the expert and novice groups (Chi-square=11.5, $p<0.01$, df=3 and Chi-square=24.5, $p<0.001$, df=3 respectively). By analyzing the pairwise comparisons, it was found that for both groups, the text only rules were rated as more difficult to understand than the other groups ($p<0.05$). There were no significant pairwise comparisons found between the other 3 presentations for experts or novices.

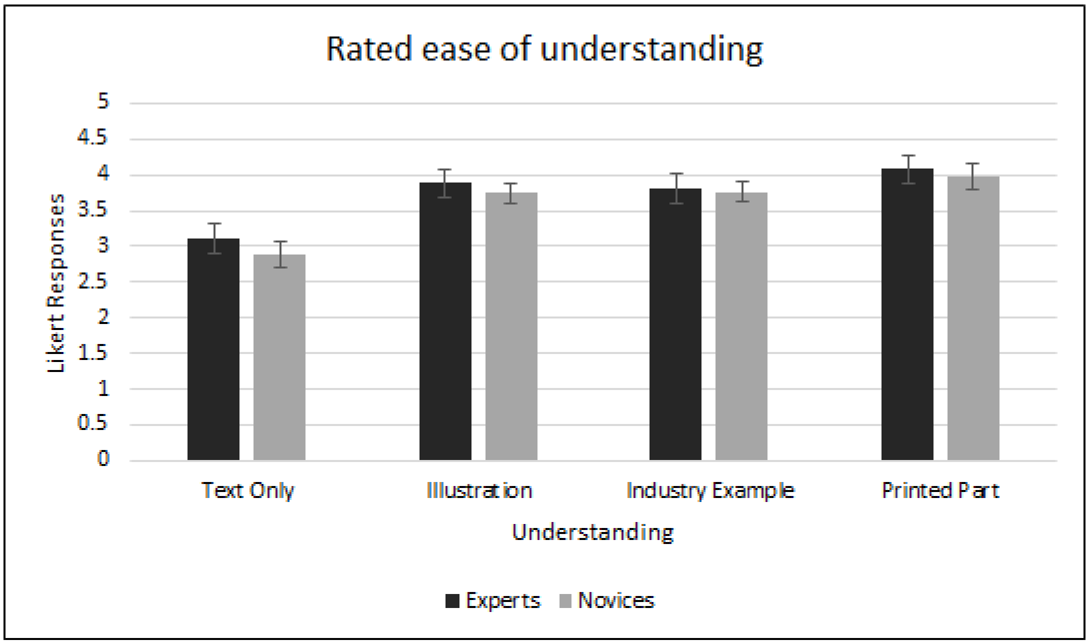


Figure 9: Rated Understanding of Design Rules of Experts and Novices. Error bars show ±1 SD

From the analysis of the effect of expertise on quality, it was found that there was no significant effect of expertise on quality ($F(1,238.2)=1.89$, $p=0.171$). Similarly, there was no significant effect of expertise on rate ease of understanding ($U=11030.5$, $p=0.606$). There was, however, a significant effect of expertise on novelty, with experts being shown to have higher novelty scores than novices ($F(1,225.4)=5.394$, $p<0.05$)

CHAPTER 5: DISCUSSION

Expert Study

Based on the above results, it was found that the experts showed no difference in their quality score based on the rule presentation modality they were exposed to. Similar results were seen for their novelty scores. On the other hand, the rule presentation modality was found to impact their perceived understanding of the rules, as the text-based presentation was rated to be the most difficult to understand. This result for quality was interesting, as it did not support hypothesis 1c (H1c) which said that quality would be higher for the non-text-based presentations, as an additional medium of presentation has generally been shown to promote learning. Deeper analysis showed that neither the individual sub-categories (Functionality, Support Material, Design Material, Number of Parts, Strength of Print) nor the aggregate quality scores yielded statistically significant differences among the conditions. One possible explanation for these quality results could be that in this case, the rules were too easy to comprehend and apply, which left very little room for the non-text-based presentations to improve performance. It is difficult to verify this within the context of this study, as the sample size is too small to separate the problems and compare them individually. However, one simple way to verify this in a future study is to perform a follow up study with a more complex set of rules. Another possible explanation could be that even when the rules were initially confusing, as participants were given ample time to solve the problems, they eventually reached a sufficient level of understanding to apply the rule correctly. This explanation is supported both by the subject's self-rated "time for ideas" and by the observation that the expert's quality and rated ease of understanding were not significantly correlated. Given that the quality scores were generally quite high, this suggests that the participants were able to get high quality scores even in problems they felt were difficult to understand. Lastly, it is worth noting that the variance in the quality scores was quite high, which is a major reason the effect of presentation was nonsignificant. Based on what was observed from the redesigns, it seems as though this was because regardless of the condition the participants were exposed to, several participants would apply the rule associated with the problem without ensuring the part would still function properly after the change. A common example of this can be seen in the juicer redesigns, where several participants increased the angle of overhang to eliminate the need for support material, without considering that the increased handle thickness would make it much more difficult to grip. Teaching designers how to balance DfAM rules with the requirements of design is evidently something that needs to be done, although incorporating this idea within every heuristic may be difficult.

Similarly, the results of novelty do not support hypothesis 1a or 1b, as it was believed that the problems in which participants were given printed parts would have the lowest novelty scores because the participants would more easily fixate on them, while the illustrations and industry examples would produce the highest novelty redesigns, but this turned out to be incorrect. Although the findings in this study do not seem to match prior expectations, there are a few things to consider. First, while physical examples can very often lead to fixation due to the very clear similarities they share with the design, in this study, the printed parts where intentionally made as abstract as possible. This likely made it more difficult for subjects to focus on the specific solutions, and instead forced them to focus on the reasoning behind them. Similarly, although the participants' text-based solutions were shown to have higher novelty than expected, several of these solutions were high-novelty, low-quality solutions which addressed the problems in unique ways, but did not properly apply the rules they were attached to. It is assumed that participants who created solutions such as these were unable to understand the purely text-based rules correctly, leading to improper application. Although this may have led to more novel solutions, it is difficult to say that this would be a positive in the context of a redesign problem if the primary goal of the redesign is not met. While this may indicate that novelty as measured in this study may not be as important for a redesign problem as it for a more typical design problem, changing the way novelty is measured could potentially affect this result. Perhaps for future studies, one way to see more novel results that are realistic would be to ask participants to generate multiple ideas and only analyze the high-quality solutions. With multiple redesigns, research suggests the likelihood of a participant producing at least one high-novelty, feasible idea naturally increases [37], meaning there would be a lower number of low-quality, high-novelty solutions in the final analysis. Ideally, this would lead to more conclusive results for novelty in future redesign studies.

The results of the self-reported ease of understanding survey data partially supports the hypothesis that 3D modalities are subjectively preferred (H1d), as although the text-based solutions were rated most difficult to understand, the results of the other three modalities were unexpected. Despite the slight preference observed for the printed parts over the illustrations and examples, the post-hoc analysis indicated it did not reach the level of statistical significance, showing that from the participants standpoint, although the text by itself was difficult to understand, all of the other modalities were perceived as equally easy to understand. This is unexpected given that the introduction of the tactile modality in addition to the visual modality would typically be expected to improve the ease of understanding. However, it is likely that their unfamiliarity with the 3D printing process hindered their ability to understand the rules being presented in this manner, which suggests the printed parts may only be particularly useful for designers who already have a reasonable understanding of the process.

Ultimately, the expert study indicated that although rule presentation does not seem to affect performance, it does seem to have an impact on the designer's perception of ease of understanding, which in many ways is equally important, as rules that are easily understood are more likely to be internalized and applied in other scenarios. Furthermore, this improved understanding was observed for all non-text modalities, suggesting that a printed part does not actually provide any additional benefit. If this is the case, there is no compelling reason to use them in the teaching process, as 2D illustrations and 3D CAD models are equivalent, while also being much easier and cheaper to create.

Novice Study

By itself, the novice study yielded no new findings, as the results seen were largely the same as those from the expert study; there was no significant effect of quality or novelty, while ease of understanding was found to be lowest for the problems with text-based rules, but not significantly different for the other three modalities. While this does serve as validation for the results of the expert study, the more notable findings from the novice study come from the comparisons which can be made between the expert and novice redesigns.

In terms of their quality scores, it was found that experts and novices did not significantly differ from each other which means hypothesis 2b (H2b) was not supported by the data. While this may initially seem odd, it is worth noting that while the experts were much more experienced in design, they were on average just as inexperienced as the novices with additive manufacturing specifically, which is made clear by their nearly identical self-ratings of their previous experience with additive manufacturing (Figure 6). Given how unique additive manufacturing rules are, it is understandable that their experience with traditional manufacturing processes did not help them much, especially considering that the problems were more focused on the correct application of DfAM rules than on generally improving the part. Furthermore, as the rules were selected to be relatively easy to understand and apply, it is expected that nearly all participants would be able to generate reasonable solutions to the problems regardless of their prior experience. The lack of a significant difference in the perceived ease of understanding of the expert and novice groups supports this explanation.

Novelty was shown to be the primary area in which experts and novices differed, with experts demonstrating significantly higher novelty scores than novices. This supports the hypothesis that experts will have more novel solutions (H2a), which makes sense, as expert designers naturally have a larger wealth of experiences to draw from, which allows them to potentially come up with more varied solutions. One notable area in which the experts demonstrated significantly higher novelty was in print orientation, as they were far more likely than novices to attempt to change the orientation of the part in order to improve its ability to print. This added dimension of design space allowed the experts to create a much wider range of designs, which is a large part of the reason their novelty scores were higher. This tendency to reorient the part can be seen particularly clearly in the soap box problem, for which over a quarter of experts reoriented the part in some way, compared to only 4% of novices.

Although in general novelty was shown to be higher for experts than for novices, it is interesting to note that for the printed parts, novelty was actually the same for experts and novices. This is interesting because it means although in the expert study there was shown to be no main effect of rule presentation modality on novelty, rule presentation modality does moderate the effect of expertise on novelty. This suggests that design fixation may be occurring for experts exposed to the printed parts, which supports the prior research [31], as well as the claim previously made that printed parts may not be the best way to present DfAM rules to AM novices. That said, research into the effects of physical parts has been far from conclusive, and while some work has been done to find the root cause [38], it is still difficult to say with certainty whether this effect plays a role in this context without additional research.

Contributions

Ultimately, the work done towards this thesis has contributed to the literature on design heuristics and design for additive manufacturing in a number of ways. First, by studying professionals from industry in addition to the students typically studied in experiments such as these, it is possible to extend the findings of this work to a larger population of designers. This is particularly important in a rapidly developing field such as additive manufacturing, in which formalized instruction is often seen even in an industry setting. Along similar lines, this thesis has added to the body of work on expert-novice comparisons, particularly in the field of design where expertise tends to come with unique connotations attached. Specifically, it has shown how expertise in one area of design can affect performance in another, which is of interest given the unique nature of design expertise. Lastly and perhaps most importantly, this work has contributed to the general understanding of design heuristics, as the question of the best way to present heuristics is one which has yet to be explored much in design literature, making this work a useful starting point for researchers interested in studying the presentation modality of design heuristics. This will be particularly important for researchers who want to make of use heuristics in an applied setting, such as part of a computational design support tool or for instructional purposes.

Limitations & Future Work

Despite the numerous potential contributions of this study, there are still a few limitations which should be considered for the sake of any future research conducted in similar areas. First, there were a few issues observed related to the sample of experts used. One issue was that the workplace used for the expert study was not as diverse as would have been desirable. Most notably, there were no females included in the expert study. While this issue was somewhat addressed by sample of the novice study which included a much more diverse set of individuals, ideally any follow-up study conducted will include a more representative sample of the general population. Furthermore, given the restricted access to the expert pool of subjects, the size of the expert sample was smaller than desired. While it is difficult to say whether this was particularly problematic in this case, it is worth noting that this does affect the ability to detect a difference, as well as the statistical power of the results. Finally, although all of the subjects from the initial study are collectively referred to as experts given that they all have several years of design/engineering experience, in reality, even within this group, there is a reasonably large amount of variance in their levels of experience. One way to capture these different levels of experience would be to further break down the expert group into sub-groups of varying expertise; however, given the already small sample size of the expert group, further sub-division is infeasible for this study, as it would only reduce statistical power more. That said, in general, there is merit in attempting to divide expertise into more than two categories as has been done in the past[35], and would be an interesting avenue to explore for future studies with larger sample sizes.

Aside from the potential issues with the samples, there are a few other limitations to the studies in this thesis. One important consideration is that ultimately one of the most important application areas of this study is in the field of education. In the context of education, while the immediate performance of the students is important, the final goal is to ensure the students are able to retain the information they learn, which can't be checked by tests that are administered while the participants still have access to the design rules. A future study with a longitudinal design that tests participants at several points in time after their initial exposure to the rule presentation could be done in the future to better cover this facet of education.

Another limitation of this study stems from the fact that the metric used to measure the ease of understanding of each participant was self-reported. While this is certainly the most direct way of determining one's attitude towards the rule presentation modalities, it does rely on participants having an accurate picture of how well they learn, which may not always be the case. For this reason, a more objective measure could be used in addition to the survey response; for example, the time it takes for each designer to complete each problem could be measured and used as a representation for how easy it was to understand/apply the rule. While this measure would surely have issues of its own, it does illustrate that other potential ways to measure ease of understanding exist, and future studies could look into using some of these other more empirical measures. While the major metric that a change like this is aimed to address is ease of understanding, a similar line of thinking could be applied to several of the survey metrics. For example, rather than simply asking how familiar participants are with additive manufacturing, the question could ask how many parts they have printed on a 3D printer, or how many different additive machines they've used. While there is always some insight to be gained from using subjective measures, objective or empirical measures are always less ambiguous and often more useful as a result.

The final limitation worth mentioning concerns the rules chosen for the studies. As was previously mentioned, the problems chosen were all fairly simple to understand and apply. This also meant they were quite easy to represent in a variety of different formats. As a result, it is difficult to say whether the findings in this thesis can be generalized to all DfAM rules, or if they are limited to simpler ones. As a result, one of the major areas for future study should be to explore a wider variety of more complex rules to see if the findings are supported.

CHAPTER 6: CONCLUSIONS

Ultimately, all of the initial research objectives identified in this thesis were addressed. For the sake of review, the research questions were:

1. How does modality of design rule presentation affect quality and novelty of DfAM redesign?
2. How do these effects vary with design expertise?

The first question has been addressed in detail by the initial expert study and was further validated by the novice study performed. Specifically, it was found that for both experts and novices, there were no significant effects of rule presentation modality on the quality or novelty of the redesign solutions. However, there was found to be a significant difference in perceived ease of understanding based on modality; specifically, the text-based rules were rated as being more difficult to understand than the illustrations, examples or printed parts. There was no significant difference found between the other three modalities. These findings are important because they give some insight into the way heuristic based instruction materials should be presented to designers. While text-based rules do not seem to reduce the participants ability to create satisfactory redesigns, they have the disadvantage of being perceived as more difficult to understand, which may certainly play a bigger role when attempting to explain more complex design rules than the ones covered in this thesis. Similarly, although printed parts are a novel way to quickly demonstrate DfAM rules, these results suggest that they have no significant advantages over illustrations or CAD examples, which suggests that they may not be worth the additional effort or cost required to produce them.

The comparison between the initial expert study and the follow-up novice study formed the basis for answering the second research question. It was found that although there was no effect of expertise on quality of redesigns or ease of understanding, experts were shown to produce higher novelty redesigns, which is understandable given their greater experience with design as a whole. This is important as it suggests that although their knowledge of traditional manufacturing did not improve their ability to design for additive manufacturing, their experience with design has improved their willingness to think of unusual solutions. Future work could focus on how instruction for novices can be adjusted to facilitate novel ideas, as it appears to be the main area in which they lag behind experts in the context of DfAM.

While both questions were addressed, there still exists a lot of room for future work in this area. The most natural follow-up to this work would be a similar experimental design but with more complex design rules to ensure that these findings apply to a wide range of design rules as opposed to the few studied here. In addition, another important follow-up study that could be performed is a longitudinal study focusing on the effects different presentation modalities have on participants' ability to retain DfAM knowledge. This is necessary to the field of education, as the long-term effects are just as important as the immediate effects. In terms of applications, the information gained from this study can potentially be applied towards the development of CAD tools that aids designers in DfAM, with the main takeaway being that text may not be the best way to represent these heuristics.

APPENDIX A: RULE PRESENTATIONS

Table 3: Rules in Text Only Format

Rule	**Justification**
If there is an overhang on the part, ensure that the angle is smaller than (Spec. 8)	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than (Spec. 9). As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.
If mating surfaces are large, add holes or pockets to one to reduce contact area.	This is to minimize the possibility of the two surfaces fusing, which is prone to happen when dealing with large surfaces. This also allows you to de-powder more easily (only applies to metal powder bed fusion).
If your part requires support structures, make sure they are not trapped inside an inaccessible volume.	This is to ensure there is some way to remove the support structures from the finished part, as they can be quite difficult to remove. This may not be needed if the supports will not interfere with the operation of the part.
If the part is larger than the build area in one dimension, either reorient it, or split the part into two.	Depending on how large the printer you have access to is, you may be limited in how large you can make your part. As a result, it can be useful to turn it into two parts and add fasteners to join them after printing.

Table 4: Rules in Illustration Format

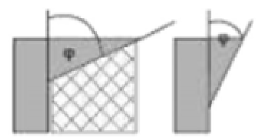
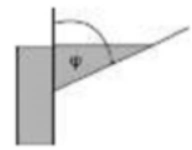
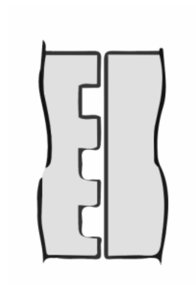
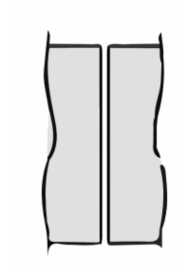
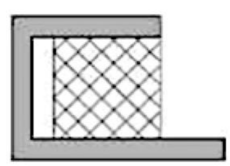
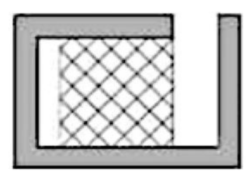
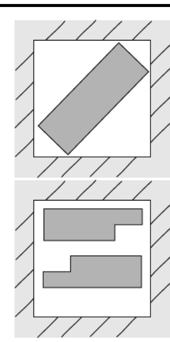
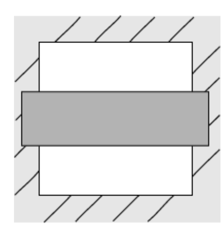
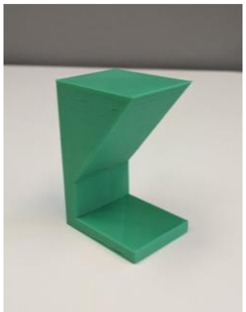
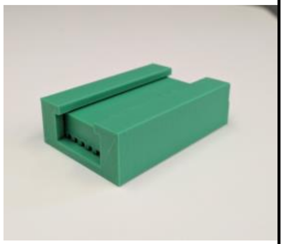
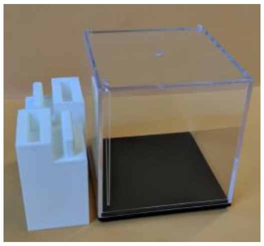
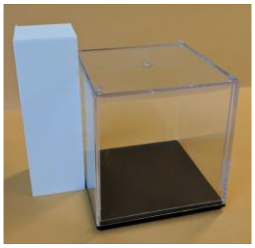
Rule	Justification	Favorable	Unfavorable
If there is an overhang on the part, ensure that the angle is smaller than (Spec. 8)	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than (Spec. 9). As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.		
If mating surfaces are large, add holes or pockets to one to reduce contact area.	This is to minimize the possibility of the two surfaces fusing, which is prone to happen when dealing with large surfaces. This also allows you to de-powder more easily (only applies to metal powder bed fusion).		
If your part requires support structures, make sure they are not trapped inside an inaccessible volume.	This is to ensure there is some way to remove the support structures from the finished part, as they can be quite difficult to remove. This may not be needed if the supports will not interfere with the operation of the part.		
If the part is larger than the build area in one dimension, either reorient it, or split the part into two.	Depending on how large the printer you have access to is, you may be limited in how large you can make your part. As a result, it can be useful to turn it into two parts and add fasteners to join them after printing.		

Table 5: Rules in Industry Example Format

Rule	**Justification**	**Favorable**	**Unfavorable**
If there is an overhang on the part, ensure that the angle is smaller than (Spec. 8)	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than (Spec. 9). As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.		
If mating surfaces are large, add holes or pockets to one to reduce contact area.	This is to minimize the possibility of the two surfaces fusing, which is prone to happen when dealing with large surfaces. This also allows you to de-powder more easily (only applies to metal powder bed fusion).		
If your part requires support structures, make sure they are not trapped inside an inaccessible volume.	This is to ensure there is some way to remove the support structures from the finished part, as they can be quite difficult to remove. This may not be needed if the supports will not interfere with the operation of the part.		
If the part is larger than the build area in one dimension, either reorient it, or split the part into two.	Depending on how large the printer you have access to is, you may be limited in how large you can make your part. As a result, it can be useful to turn it into two parts and add fasteners to join them after printing.		

Table 6: Rules in Printed Part Format

Rule	**Justification**	**Favorable**	**Unfavorable**
If there is an overhang on the part, ensure that the angle is smaller than (Spec. 8)	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than (Spec. 9). As a result, if you are trying to avoid the use of supports, try to design the part in a way that keeps overhangs as close to vertical as possible.		
If mating surfaces are large, add holes or pockets to one to reduce contact area.	This is to minimize the possibility of the two surfaces fusing, which is prone to happen when dealing with large surfaces. This also allows you to de-powder more easily (only applies to metal powder bed fusion).		
If your part requires support structures, make sure they are not trapped inside an inaccessible volume.	This is to ensure there is some way to remove the support structures from the finished part, as they can be quite difficult to remove. This may not be needed if the supports will not interfere with the operation of the part.		
If the part is larger than the build area in one dimension, either reorient it, or split the part into two.	Depending on how large the printer you have access to is, you may be limited in how large you can make your part. As a result, it can be useful to turn it into two parts and add fasteners to join them after printing.		

APPENDIX B: DESIGN PROBLEMS

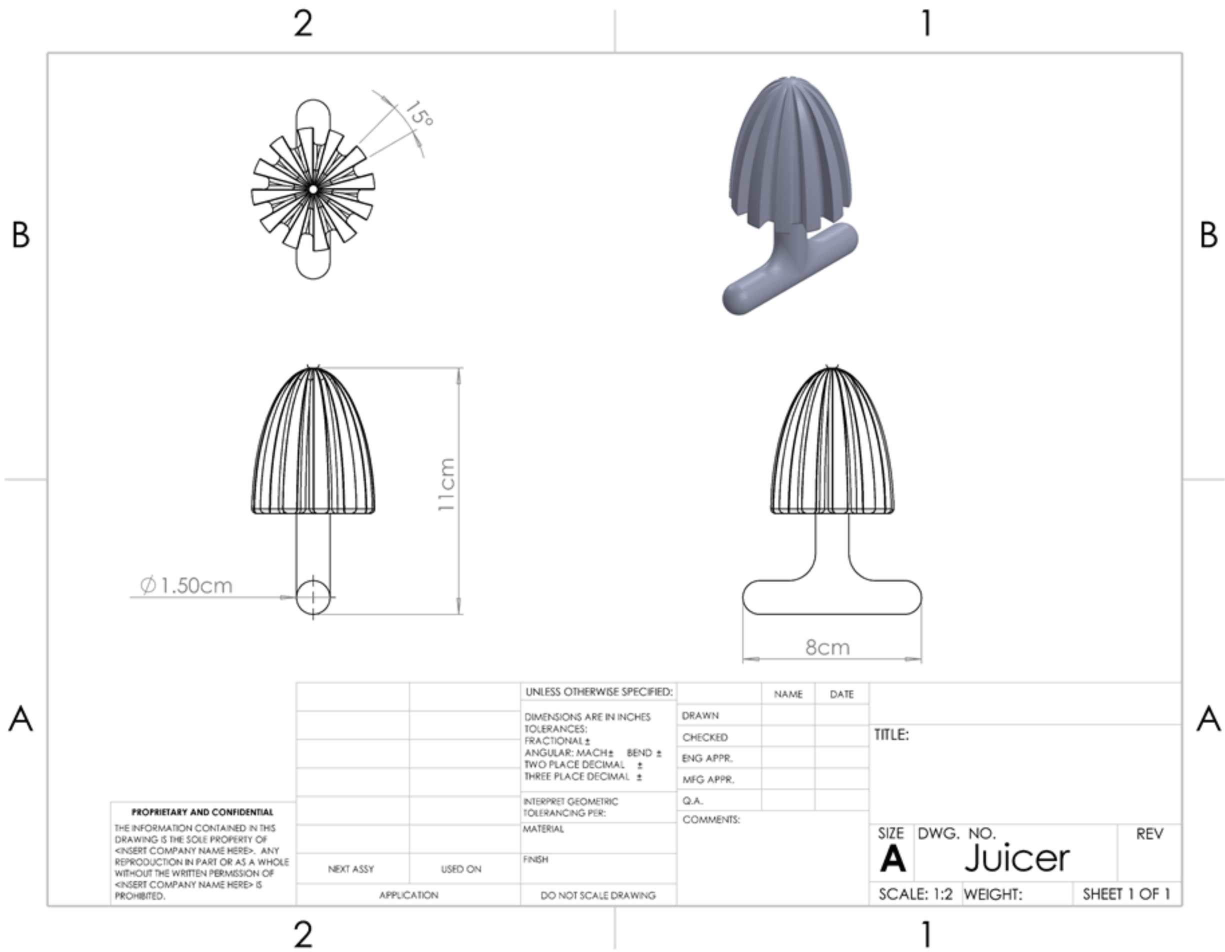


Figure 10: Overhang problem. “Handheld juicer to extract juice from small citrus fruits.”

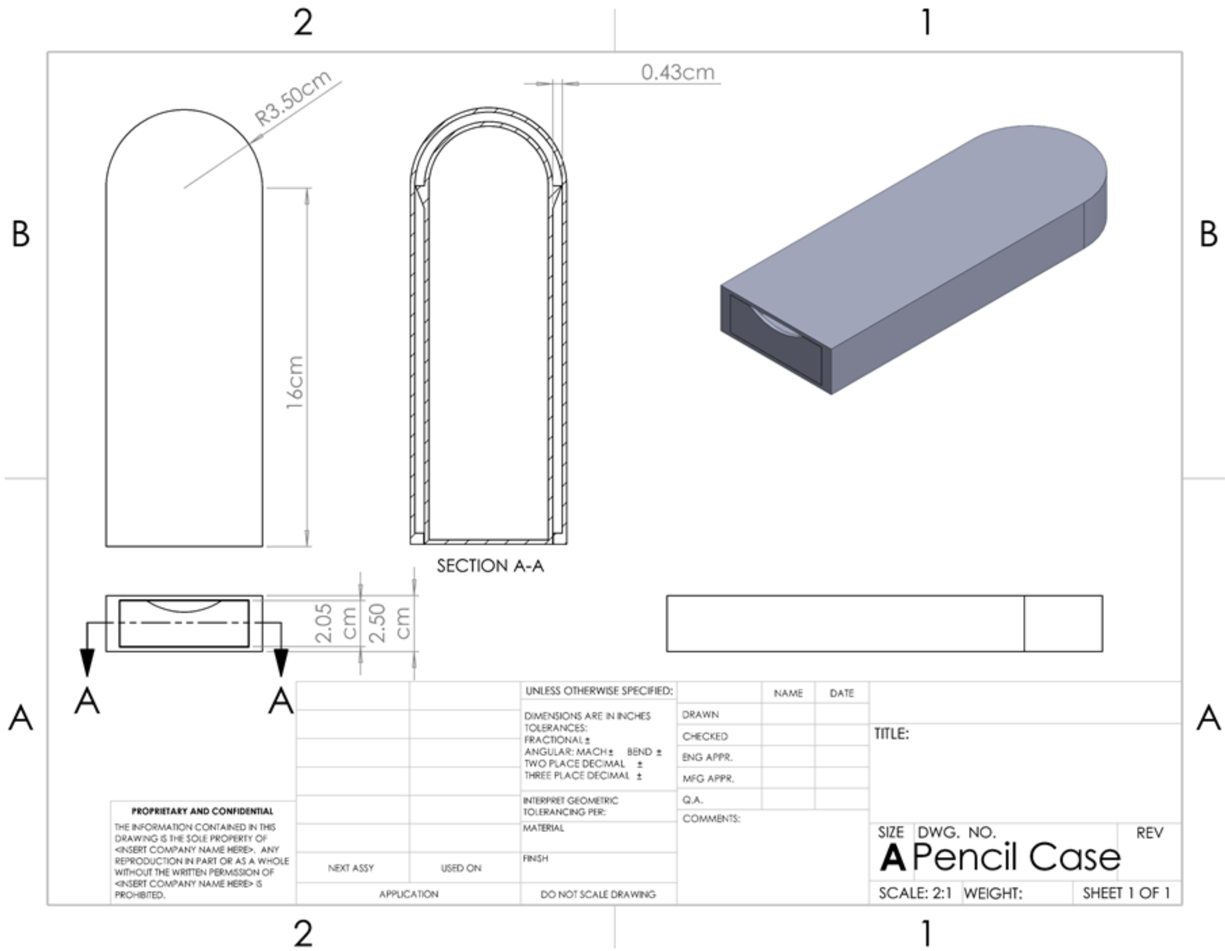


Figure 11: Prismatic joint problem. “Pencil case: The drawer is blocked off so that it cannot fully come out of the case.”

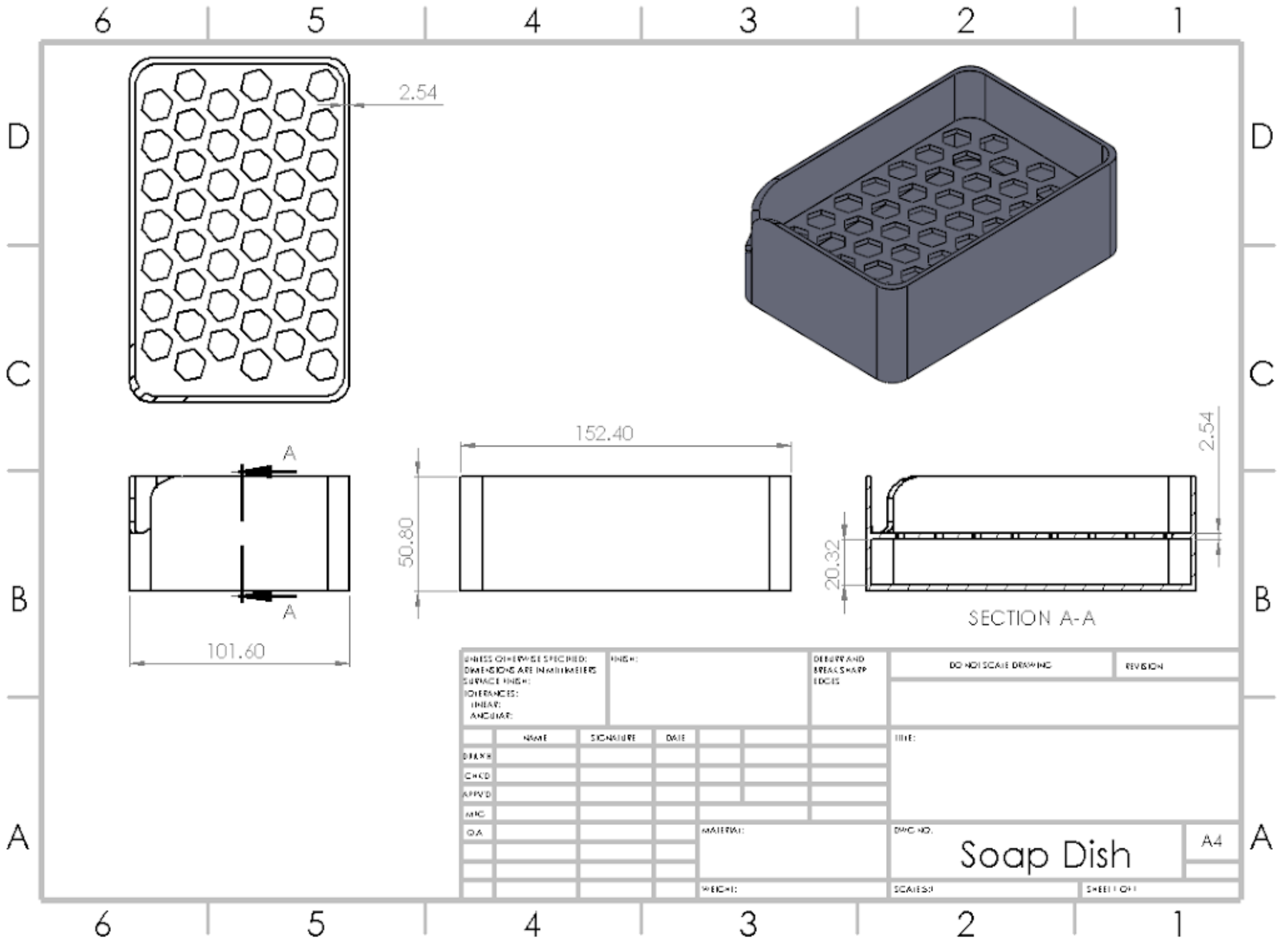


Figure 12: Trapped support problem. “Soap dish with hexagonal drainage holes to prevent puddle buildup around the soap. All dimensions are in millimeters.”

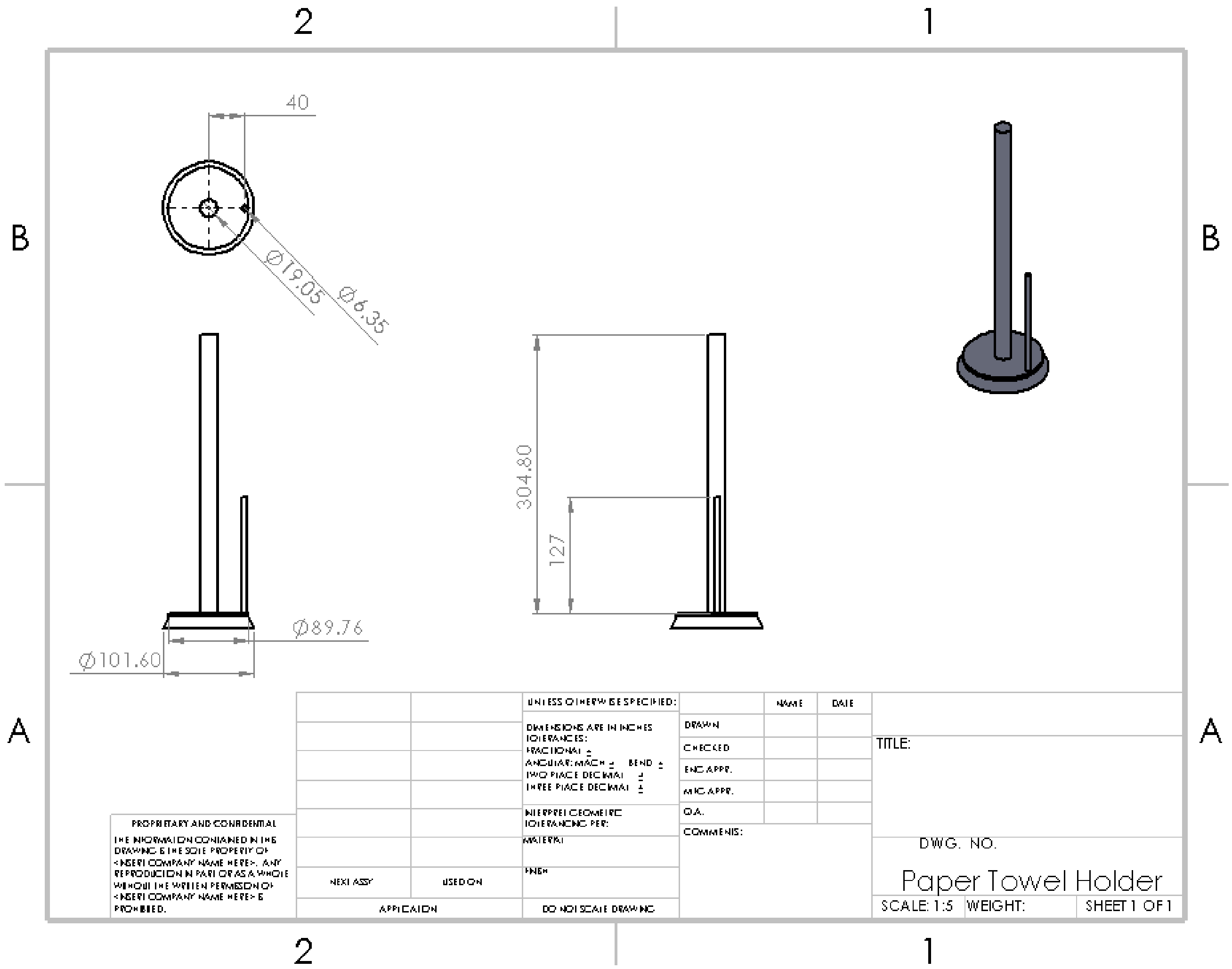


Figure 13: Part Size Problem. “Paper towel holder: the paper towel roll fits over the main the large rod, with the smaller rod used for removing individual towels.”

APPENDIX C: SHORT COURSE OUTLINE

Design for Additive Manufacturing (AM) Course Outline
One-Day Short Course (8 hrs)
David Rosen and Carolyn Seepersad

I. Overview of AM and AM Processes (1 hr)

A. Overview of AM industry and market size
B. Review/description of the 7 ASTM categories of AM processes
C. Example applications of AM processes

II. Selection of AM processes (1.5 hr)

A. Criteria for selecting AM versus conventional fabrication
B. AM selection process/tool
    a. Selection exercise

III. Conceptual Design for AM (2 hr)

A. Design exemplars for ideation
    a. Short redesign exercise
B. Topology optimization
    a. Hands-on exercise with topology optimization software (if available)

IV. Detailed Design for AM (2 hr)

A. AM workflow
B. Costing and build time estimation
C. AM material properties (repeatability, anisotropy)
D. Design guidelines
    a. Design mini-project

V. Special topics (1 hr)

A. CAD/CAE tools for AM (if CAD is available for attendees)
B. Lattice structures
C. Future of AM

APPENDIX D: NOVICE LECTURE OVERVIEW

Adapted from content developed by David Rosen and Carolyn Seepersad

Introduction to Design for Additive Manufacturing

Part 1

ME1770

1

Learning Objectives

- Learn about different types of AM
- Learn about the unique capabilities of AM
- Learn about how industries have taken advantage of the unique capabilities of AM
- Understand the characteristics of designs that favor AM
- Learn about the design for AM process

2

Additive Manufacturing – 3D Printing

- ASTM definition of AM: The process of joining materials to make objects from 3D model data, usually layer-by-layer, as opposed to subtractive manufacturing methodologies
- Other terminology: 3D printing, rapid prototyping, rapid manufacturing, direct digital manufacturing, solid freeform fabrication

THE GEORGE W. WOODRUFF SCHOOL OF MECHANICAL ENGINEERING

3

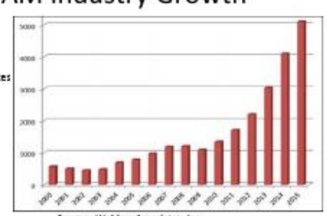
4

ASTM-ISO Standard Processes

- Vat Photopolymerization (SLA) – 3D Systems
- Powder Bed Fusion (SLS) – 3D Systems, Arcam, Concept Laser, EOS, Renishaw, SLM Solutions
- Material Extrusion (FDM) – Stratasys
- Binder Jetting (3DP) – 3D Systems, Ex One, HP
- Material Jetting – 3D Systems, Objet
- Directed Energy Deposition – Optomec, DM3D, InssTEK
- Sheet Lamination – Mcor Technologies, Fabrisonic

5

AM Industry Growth



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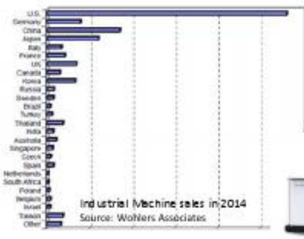
1

Industrial Machine Sales



Industrial Machine sales in 2014
Source: Wohlers Associates

7

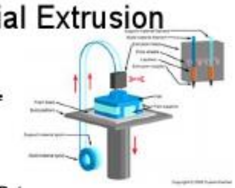
Additive Manufacturing Processes

	1-D		2-D
	Scanning	Parallel	Area Filling
Pattern Material	Matl Extrusion	Matl Jetting Binder Jetting	Thermal Spray
Pattern Energy	Vat Photopoly (laser) PBFusion (polymer, metal) Electrochemical Deposition		Vat Photopoly (mask projection) Sheet Lamination (paper, foam, metal, ceramic)
Pattern both Material & Energy	Directed Energy Deposition		

8

Material Extrusion

- Process Characteristics
  - A heated thermoplastic filament is extruded from a capillary die
  - Parts chamber is heated to minimize stresses and deformation
  - Requires support structures
- Stratasys, 3D Systems, Makerbot, RepRap, PrintRBot, etc.



Stratasys 900mc

9

Material Extrusion – 3D Printers

$500 – $3k

Afinia

MakerBot Replicator

Rostock
(http://reprap.org/wiki/Rostock)

Cube,
3D Systems

10

Fiber-Reinforced Composites

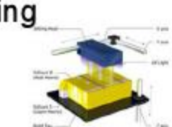
- MarkForged
- Carbon fiber, fiberglass,

- Arevo Labs
- Carbon fiber layup on

11

Material Jetting

- Process Characteristics
  - Nozzles jet beads of wax or photopolymer.
  - As easy to use as a network printer.
  - Fast and inexpensive.
  - Extensive support structures needed.



The Objet PolyJet Process

- 3D Systems, Solidscape, Stratasys

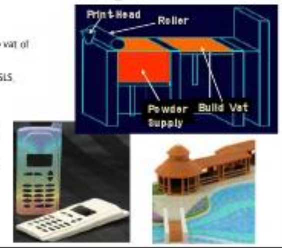
Eden 250 from Objet Geometries

12

2

Binder Jetting

- **Process Characteristics**
  - Print head deposits binder into vat of powder.
  - Powder recoating is similar to SLS
  - Fast and inexpensive.
  - Fragile and limited accuracy
    - good infiltrants available
- **Z Corporation (3D Systems), SolidScape, Extrude Hone, Voxellet, HP**



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Additive Manufacturing Processes

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	Scanning	Parallel	Area Filling
Pattern Material	Matl Extrusion	Matl Jetting Binder Jetting	Thermal Spray
Pattern Energy	Vat Photopoly (laser) PBFusion (polymer, metal) Electrochemical Deposition		Vat Photopoly (mask projection) Sheet Lamination (paper, foam, metal, ceramic)
Pattern both Material & Energy	Directed Energy Deposition		

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Powder Bed Fusion

- Selective Laser Sintering (SLS)
  - Laser fuses powders in layers using a computer controller scanning system
  - Powder is replenished and the next layer is scanned
  - Powder temperature is maintained near melting point to aid fusion and minimize distortions
  - Supports needed for metal
- EOS, 3D Systems, Arcam, Concept Laser, Renishaw, SLM Solutions
- $300k - $1M

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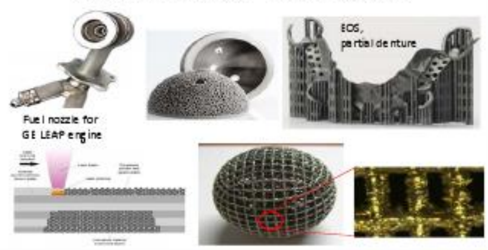
Metal Powder Bed Fusion



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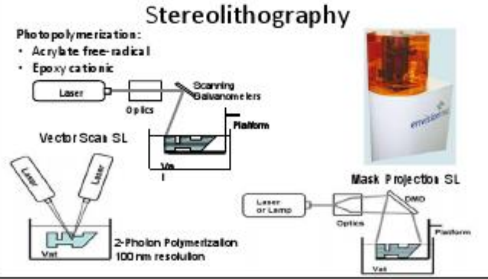
Polymer Powder Bed Fusion

- Polyamide (Nylon), glass-filled polyamide, elastomer, PEEK/PAEK, PS, composites
- Largest powder bed: 550x550x750 mm (sPro 230), 700x380x560 (P800)

17

Stereolithography

Photopolymerization:
- Acrylate free-radical
- Epoxy cationic



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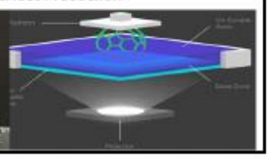
Carbon3D

- Fast mask-projection stereolithography process
- Utilizes oxygen inhibition to prevent cured resin from sticking to window.
- CLIP = Continuous Liquid Interface Production



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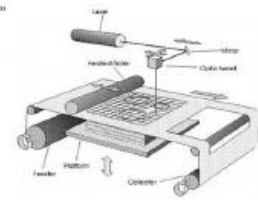
Sheet Lamination/Laminated Object Manufacturing (LOM)

- Process Characteristics
  - A CO_2 laser cuts thin sheets of material into desired cross-sections
  - Process is tuned to precisely cut to sheet thickness
  - Material is thermally fused to the previous layer using a heated roller
  - Diced material is removed to uncover completed parts
- Mcor Technologies
- Helisys (out of business, 1999).
- Related Technologies
  - Cubic Technologies, Sparx, Kira, Fabrisonics



20

Applications of LOM

- Large, bulky parts
- Patterns for sand casting
- Visual prototypes

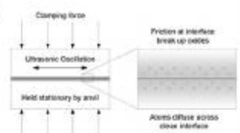
Helisys

Mcor Tech. Iris

21

Ultrasonic Consolidation

- Process Characteristics
  - Uses sonic welding to fuse aluminum strips to one another to add a layer.
  - Machines contours of layers (3 axis machine tool).
  - Titanium alloys also.
  - Can embed components - fiber optics for sensing.
- Solidica, Inc.; Fabrisonic



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Additive Manufacturing Processes

	1-D		2-D
	Scanning	Parallel	Area Filling
Pattern Material	Matl Extrusion	Matl Jetting Binder Jetting	Thermal Spray
Pattern Energy	Vat Photopoly (laser) PBFusion (polymer, metal) Electrochemical Deposition		Vat Photopoly (mask projection) Sheet Lamination (paper, foam, metal, ceramic)
Pattern both Material & Energy	Directed Energy Deposition		

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Directed Energy Deposition

- Process Characteristics
  - Direct metal fabrication using laser cladding process.
  - 550W and 1000W Nd:YAG lasers.
  - Materials: 316 and 304 stainless steels, H13 tool steel, nickel-based superalloys such as Inconel 625, 690, and 718, 2024 aluminum, and Ti-6Al-4V titanium alloy .
  - 5-axis deposition head available.
- Laser Engineered Net Shaping (LENS) Optomec, developed at Sandia
- Related Technologies
  - DM3D, Sciaky

Optomec 850

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Design for Additive Manufacturing

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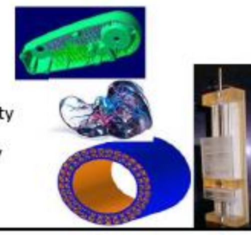
AM Unique Capabilities

- Shape Complexity
- Material Complexity
- Hierarchical Complexity
- Functional Complexity



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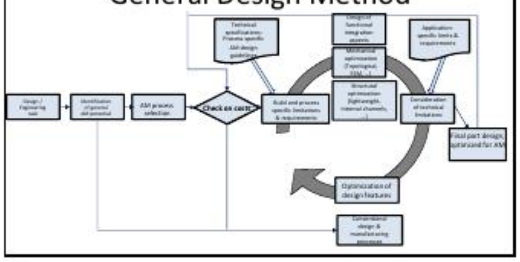
General Design Method



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Design Opportunities

- **Part consolidation – replace several parts with 1**
  - reduced assembly operations & tooling
  - reduced inventory
- **Complex geometries**
  - more efficient designs, better integration
  - lightweight structures
- **Custom geometries**
  - custom medical devices
  - custom products
  - low volume, economical production
  - agile manufacturing

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Design Opportunities (contd.)

- **Multi-materials, Multi-functionality**
  - lightweight
  - part consolidation, integration
- **No tooling – fewer manufacturing processes**
  - agile manufacturing
  - enables distributed manufacturing
- **Efficient usage of materials**
  - less waste, cost
- **Less energy consumption during processing; smaller carbon footprint (low production volumes)**

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Purposes of AM Parts

- **Prototypes**
  - Concept – look/feel of product
  - Form/Fit – assemble the product, identify clearances & interferences
  - Functional – operational part/product
- **Production Manufacturing**
- **Tooling**

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Design Guidelines for Additive Manufacturing

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Process-Specific Design Guidelines

- Many rules of thumb have been developed for each process
- And each machine
- Rules can be material dependent
- Primary process variables
  - Part orientation
  - Layer thickness
  - Support structures/anchors (yes/no)

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Support Structures

- **Processes requiring supports**
  - Material extrusion
  - Vat photopolymerization
  - Material jetting
  - Metal powder bed fusion
  - Sheet lamination (metal)
- **Process that do not require supports**
  - Polymer powder bed fusion
  - Binder jetting
  - Directed energy deposition
  - Sheet lamination (paper?)

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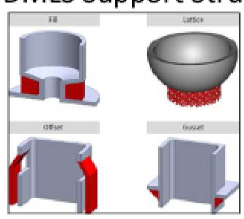
DMLS Support Structures



Xometry DMLS Design Guide 2014-2015

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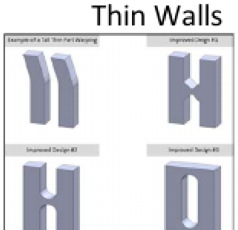
Thin Walls



Xometry DMLS Design Guide 2014-2015

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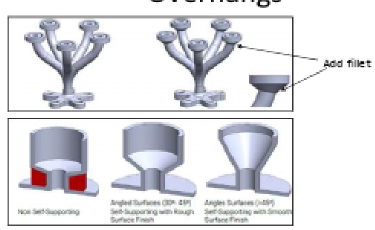
Overhangs



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6

General Design Rules

	Favorable	Unfavorable	Explanation
Part Size			If the length, height r thickness of a part are larger than or equal to the corresponding length, height and thickness of build volume, then the part is over-sized. If the part is oversized, then it could be split into two or more smaller parts.
Adjacent Parts			If there is more than 1 STL file and if the distance between the parts is less than a threshold, then the STL files should be combined into 1 single file.
Surface quality (e.g. staircase effect), final machining			If the surface angle is not 0° or 90°, then the surface will have the staircase effect. If the surface roughness is larger than a threshold, then surface machining is required.

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General Design Rules

Minimize contact area between parts	Favorable	Unfavorable	Rule, Explanation
Planar surfaces, prismatic joints			If mating surfaces are large, then add holes or pockets to one to reduce contact area.
Revolute joints			If there is a revolute joint with a long bushing, then split the bushing to prevent fusion and enable depowdering.
Spherical joints, ball bearing			If there is a spherical joint and the socket is solid, then add holes to prevent fusion and enable depowdering.

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General Design Rules

Cavities	Favorable	Unfavorable	Rule, Explanation
Accessible Support Structures			If a geometry contains a closed or inaccessible volume, and if there is support structure, then there is trapped support structure inside. If trapped support structure, then modify the part geometry to ensure support structure can be removed.
Trapped Volume, Material removal			If part geometry causes a closed volume, then material will be trapped. If material is trapped, then add hole(s) to enable material removal.
Trapped Complex Volume, Material removal			If the trapped volume has a complex shape, then add additional holes to enable depowdering or material removal.

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General Design Rules

Minimum Feature Sizes	Example	Capabilities, Limitations
Thin Wall		t > min. feature threshold h/t < aspect ratio threshold For slanted wall, t > min. feature threshold at θ degree angle h/t < aspect ratio threshold at θ degree angle
Minimum Hole Size		d > min. hole threshold For thick walls, the minimum hole threshold will increase For slanted wall, d > min. feature threshold at θ degree angle

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General Design Rules

Minimum Feature Sizes	Example	Capabilities, Limitations
Thin Column		t > min. or d > min. feature threshold h/t < aspect ratio threshold For slanted column, t > min. (or d > min.) feature threshold at θ degree angle h/t < aspect ratio threshold at θ degree angle
Minimum Groove Width		w > min. groove threshold For deep grooves, the minimum groove threshold will increase For slanted grooves, w > min. feature threshold at θ degree angle
Maximum Overhang Distance		w < maximum overhang distance threshold
Maximum Unsupported Bridge		w < maximum unsupported bridge distance threshold

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General Design Rules

	Favorable	Unfavorable	Explanation
Hole features – Surface quality, final machining			If there is a hole, and if the hole axis' angle is not 90°, then it is a hole-to-be-undersized.
	No hole		If there is a hole-to-be-undersized, and if the diameter of the hole is smaller than a threshold, then it is a hole-to-be-removed.
Print orientation of large flat surface/wall			If the thickness / length or thickness / height ratio of a part is smaller than a threshold, then the "length-height" surface is a large flat surface. If there is a large flat surface, then the surface angle of the large flat surface should be 90°.

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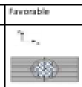
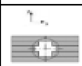
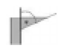
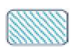
FDM & Metal Powder Bed Fusion

	Favorable	Unfavorable	Explanation
Hole features – Support material			If the hole axis' angle is smaller than a threshold, then support structure may be required to build the hole. If a hole's diameter is less than the minimum support threshold, then the hole does not need support structure.
Overhangs			If the surface angle of a feature is down-facing and greater than 0, then the surface forms an overhang. If the surface angle of an overhang is smaller than an angle threshold, then support structure is required.
Infill			The inside of the part could be chosen not to be 100% solid infill (set up -> fill option), based on what the part is used for, in order to reduce printing time and material cost.

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Reminders

- Individual 3D Printer Project – 15-20 Ideation Sketches
- Teapot Lab
  - Solidworks part file (Canvas)
  - PDF drawing file (Canvas and bring paper copy of drawing)
- Individual 3D Printer Project – CAD and STL models

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8

Introduction to Design for Additive Manufacturing

Part 2

ME1770

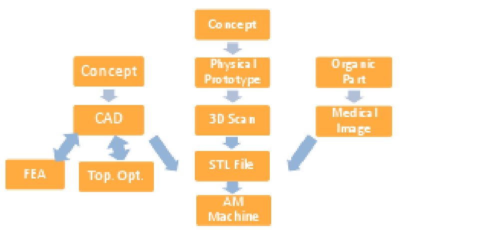
1

Learning Objectives

- Learn about design for AM guidelines
- Describe how to design parts for 3D printing adjusted for tolerances
- List a process for designing 3D printed connections
  - Find solutions (reverse engineering, etc)
  - Design in CAD accounting for tolerances

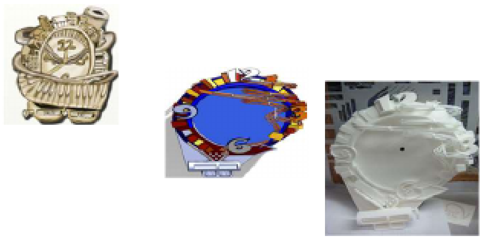
2

Potential Workflows from Idea to Product



3

Concept to CAD to STL



4

CAD to STL File

- All popular CAD software exports files as STL files.
  - Create the solid model in CAD software (saving it in the native CAD software format)
  - Export the file as an STL file when the solid model is ready for AM
  - Changes to part typically made in CAD software before conversion to STL
  - When converting to STL, pay particular attention to resolution of STL file (tradeoff between resolution and file size)

5

STL File Format

STL file in ASCII (typically saved in Binary form)

A few sides of a cube

```
solid cube_corner
  facet normal 0.0 -1.0 0.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 1.0 0.0 0.0
      vertex 0.0 0.0 1.0
    endloop
  endfacet
  facet normal 0.0 0.0 -1.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 0.0 1.0 0.0
      vertex 1.0 0.0 0.0
    endloop
  endfacet
  facet normal -1.0 0.0 0.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 0.0 0.0 1.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
```

6

1

STL File Preparation for AM

- STL files must be checked and repaired before sending to AM machine
  - Common errors with STL files
    - Non-manifold geometry
    - Holes
    - Inverted normals
    - Poor aspect ratios
  - Common software for checking and repairing STL files
    - Netfabb Basic: Free download; repairs stl files

7

Converting Solidworks Files to .stl

- File>Save as>Save as type ".stl"
- Click "Options"

8

Representational Errors

Different resolution specified for STL file conversion

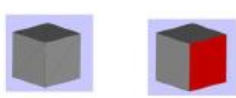
9

STL File Error: Poor Resolution

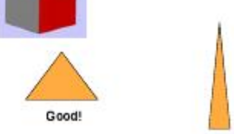
10

STL File Error: Inverted Normal

Objet.com



Also, degenerative triangles, aka poor aspect ratios

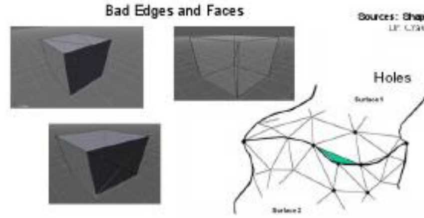


11

STL File Error: Holes and Bad Edges

Bad Edges and Faces

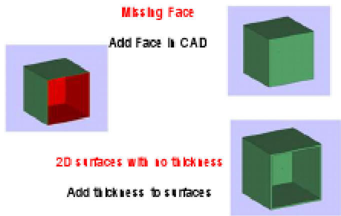
Sources: Shapeways.com



12

2

STL File Errors: Other Geometry Errors



13

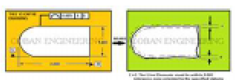
How do you learn to design connecting parts?

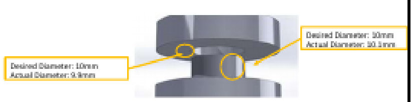
- Reverse Engineering
  - Toys
  - Thingiverse
- Experimentation (Trial and error)
- Ask an Expert
- Books
  - Great for threads, but not other types of plastic connections

14

Tolerances and Nominal Size

- In the real world there are no 'ideal' machining operations capable of producing 'perfect' parts
  - Tolerances are used to control the variation that exists on all manufactured parts
- 3D printed parts are no exception





15

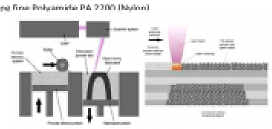
What will affect the accuracy of 3D printed parts?

- Resolution of the 3D printer (accuracy)
  - X-Y resolution is different from the z-axis resolution
- Conversion of Solidworks file to .stl and the settings
- Manufacturing variance
- Aging and abuse to the printers
  - Probably will not be an issue

16

Individual Project

- Selective Laser Sintering (SLS)
  - Type of 'powder bed' 3D printing
  - High power laser is used to 'selectively' fuse small particles of plastic, ceramic, glass, or metal
- EOS Formiga P110
  - Using fine Polyamide PA 2200 (Nylon)

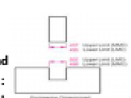


17

Individual Project Tolerancing

- EOS Formiga P110 – Basic Characteristics
  - 3D printed parts have a tendency to shrink (not always)
  - Tolerance: 0.1-0.2 mm
  - Min. thickness: 0.6 mm (X-Y), 0.1 mm (Z)
  - Min. gap between components/features: 3-5mm

- Tightly fitting parts that will not undergo relative motion and are not expected to be frequently assembled/disassembled: ~0.2-0.3 mm size difference (close to a Clearance Locational or a Transition Locational fit)



18

3

Basic 3D Printing Guidelines – Feature Size

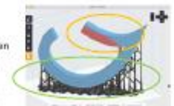
Looks pretty good, right? Wrong!

- All features should be at least ~1.0 mm in thickness
- Possible exception – text, decorative inlays, etc.
- Major structural elements (walls, interlocking features, etc.) should be thicker
- Utilize the sample SLS parts to estimate mechanical properties of the features in your own design

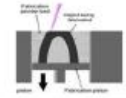
19

Basic 3D Printing Guidelines – Support Structures / Overhangs

- 3D printing is an additive process – each layer is consequently added to the previous layer
- Support structures is 'scaffolding' that is often needed when there is no existing material layer to support the next one
- Frequently required for FDM prints
- Increase material expenditure, can be difficult to remove, parts often require cleaning



Support structures are NOT needed for SLS printing, since all part features are suspended in a 'bath' of build material (Nylon powder) during the print process

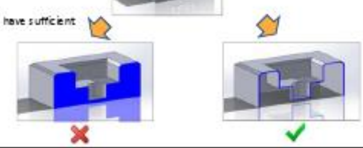


20

Basic 3D Printing Guidelines – Hollow Parts

- Hollow parts are generally preferred over solid ones
  - Material expenditure reduced
  - Often print faster

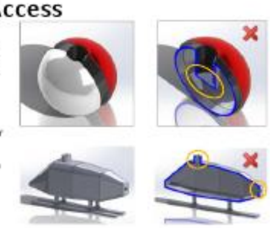
- Ensure that walls have sufficient thickness



21

Basic 3D Printing Guidelines – Interior Access

- Avoid producing hollow parts with a 'watertight' interior
  - Frequently the result of a 'Shell' operation with none of the CAD model faces selected
  - Loose plastic powder is trapped within the finished part – cannot be recovered
- Make sure that openings to the part interior are of sufficient size
  - Removing 6 in^3 of powder through a 2 mm hole is not fun
- Alternative solutions?

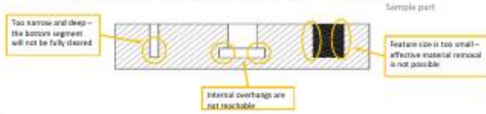


22

Basic 3D Printing Guidelines – Feature Cleanup

- SLS-produced parts are post-processed in an abrasive blasting cabinet - to remove loose and partially-sintered plastic powder
- Special consideration should be given to the ease of access to the features that will require blasting to be fully functional

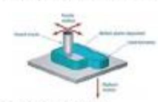
Sample part



23

Printers in the Invention Studio Fused Deposition Modeling (FDM)

- The part is produced by extruding molten material to form layers as the material hardens immediately after extrusion from the nozzle.
- Basic Characteristics:
  - Low-quality surface finish
  - Better mechanical properties
  - Plastics as raw material (PLA is used in the Invention Studio)



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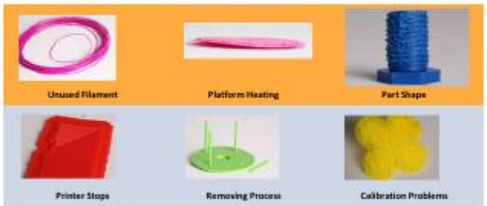
4

Common Types of Failures of FDM



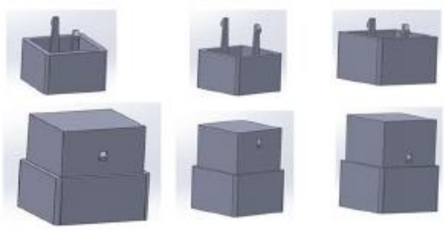
Design Guidelines for FDM:
https://www.stratasysdirect.com/resources/fused-deposition-

25

Parts Demo
Types of Connections

26

Snap-fit



27

Snap-fit pivot

28

Gears

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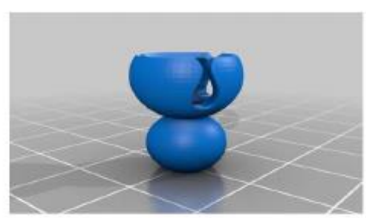
Ball Joint



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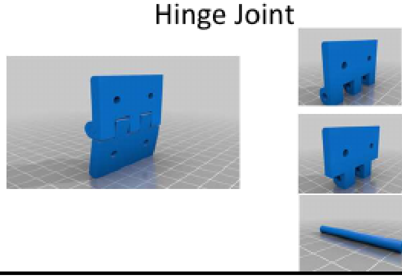
5

Hinge Joint



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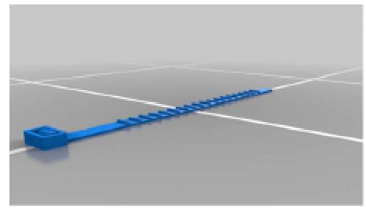
Zip Tie



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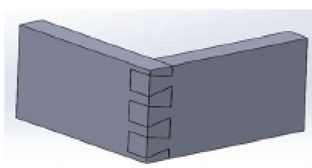
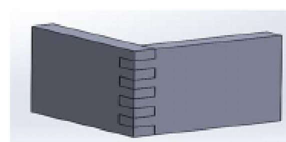
Dovetail Joint



33

Comb/Finger Joint



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Reminders

- Individual 3D Printer Project – 15-20 Ideation Sketches
- Teapot Lab
  - Solidworks part file (Canvas)
  - PDF drawing file (Canvas and bring paper copy of drawing)
- Individual 3D Printer Project – CAD and STL models

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APPENDIX E: STUDY INSTRUCTIONS

DFAM Design Prompt and Tasks

Consider the following design:

Objective: Use sketching to revise the given design using the design for additive manufacturing (DFAM) rules presented during the workshop. The redesign should be better suited for additive manufacturing than the original design. Take the next 5-10 minutes to generate concepts for solving this design problem. Use notes for additional description as necessary and label any added or modified parts to the design.

Important printer Specs for Stratasys Fortus 900mc FDM printer:

1. Build volume (XYZ): 200mm x 200mm x 200mm
2. Minimum wall thickness: 1.02mm
3. Minimum hole diameter: 0.25mm
4. Maximum non vertical unsupported hole diameter: N/A*
5. Minimum groove width: 0.25mm
6. Maximum unsupported bridge length: 25mm
7. Minimum Joint Clearance: per geometry basis
8. Maximum unsupported overhang angle: 40^{o}
9. Maximum unsupported horizontal overhang length: 1mm

APPENDIX F: POST-STUDY SURVEY

The following are general demographic questions as well as questions relating to your experience in the Design for Additive Manufacturing (DFAM) workshop

What is your age?

- ❍ 18-20
- ❍ 21-23
- ❍ 24-26
- ❍ 27-30
- ❍ 31-35
- ❍ 36-40
- ❍ 41-50
- ❍ 51-60
- ❍ 61-70
- ❍ 71-80
- ❍ 80+

What is your gender?

- ❍ Female
- ❍ Male
- ❍ Other - Please Specify ____________________
- ❍ Prefer not to say

How would you classify yourself? (Select all that apply)

- ❑ Arab
- ❑ Asian/Pacific Islander
- ❑ Black
- ❑ Caucasian/White
- ❑ Hispanic
- ❑ Indigenous or Aboriginal
- ❑ Latino
- ❑ Multiracial
- ❑ Would rather not say
- ❑ Other ____________________

How long have you been working for your company? (years)

How many years of design experience do you have?

How many years of engineering experience do you have?

What higher education degrees to you hold, and in what field(s) did you earn them? (e.g. B.S. in Mechanical Engineering)

Degree/Field of Study 1
Degree/Field of Study 2
Degree/Field of Study 3
Degree/Field of Study 4
Degree/Field of Study 5
Degree/Field of Study 6

What is your current job title?

How experienced were you with additive manufacturing before this workshop?

	Very Experienced	2 (2)	3 (3)	4 (4)	Completely inexperienced
	❍	❍	❍	❍	❍

How confident are you in your design for additive manufacturing ability after this workshop?

- ❍ Not Confident
- ❍ Somewhat Confident
- ❍ Confident
- ❍ Very Confident

I had enough time to come up with ideas:

- ❍ Strongly Agree
- ❍ Agree
- ❍ Neither agree nor disagree
- ❍ Disagree
- ❍ Strongly Disagree

How comfortable are you at sketching your ideas?

- ❍ Extremely comfortable
- ❍ Somewhat comfortable
- ❍ Neither comfortable nor uncomfortable
- ❍ Somewhat uncomfortable
- ❍ Extremely uncomfortable

How challenging did you find the design problems?

	Extremely challenging	Very challenging	Moderately challenging	Slightly challenging	Not challenging
Design Problem 1	❍	❍	❍	❍	❍
Design Problem 2	❍	❍	❍	❍	❍
Design Problem 3	❍	❍	❍	❍	❍
Design Problem 4	❍	❍	❍	❍	❍

How easy were the following design rules to understand.

	Extremely easy	Somewhat easy	Neither easy nor difficult	Somewhat difficult	Extremely difficult
Rule 1 (Overhangs)	❍	❍	❍	❍	❍
Rule 2 (Prismatic joints)	❍	❍	❍	❍	❍
Rule 3 (Accessible Support Structures)	❍	❍	❍	❍	❍
Rule 4 (Part Size)	❍	❍	❍	❍	❍

Overall, how effective do you think this workshop was?

❍ Very Ineffective
❍ Somewhat Ineffective
❍ Neither Effective nor Ineffective
❍ Somewhat effective
❍ Very Effective

APPENDIX G: SAMPLE REDESIGNS

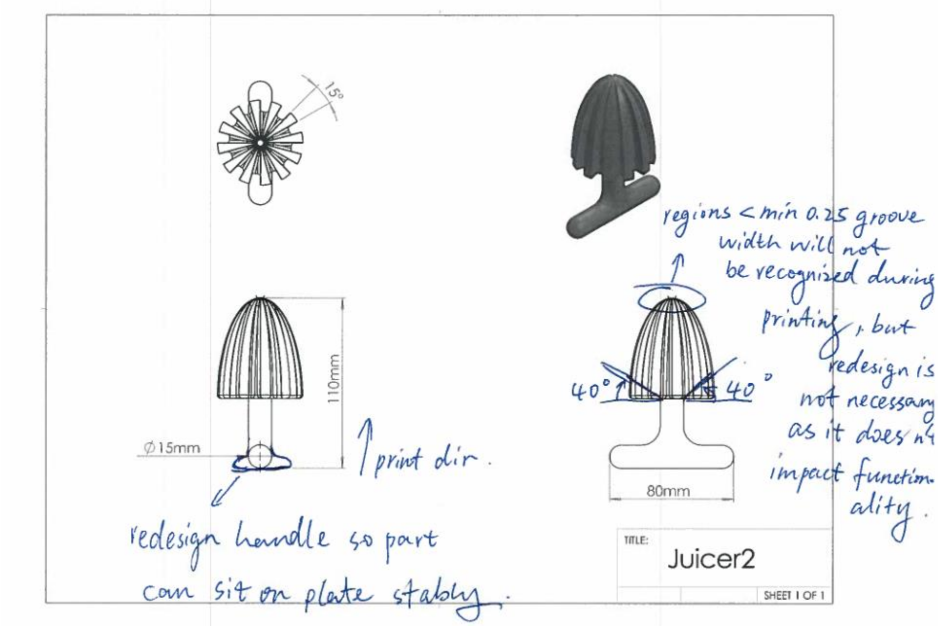

Figure 14: High Quality Juicer. Design Material: 0. Support Material: 1. Number of Parts: 1. Functionality: 1. Strength of Print: -1.

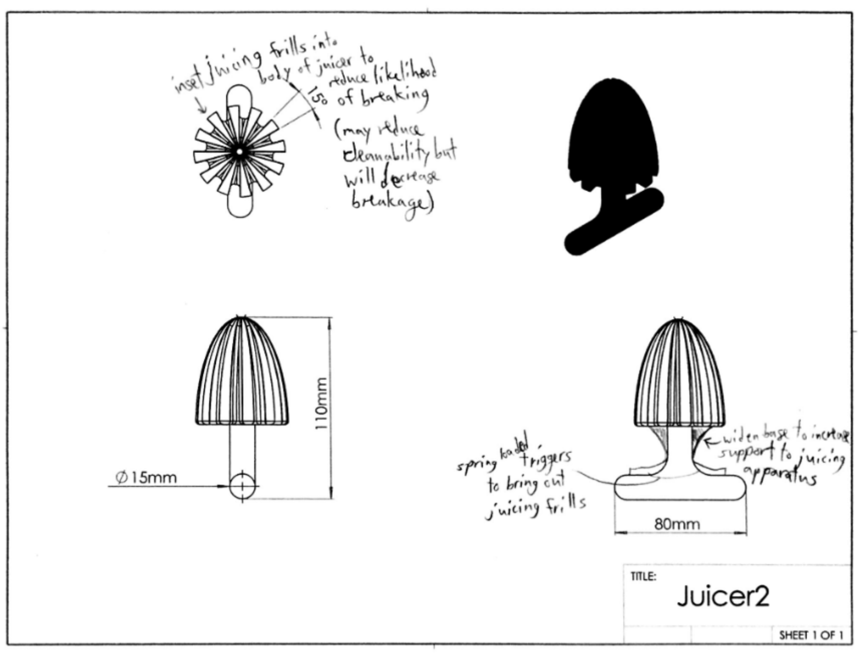

Figure 15:Low Quality Juicer. Design Material: -1. Support Material: 1. Number of Parts: -1. Functionality: -1. Strength of Print: -1.

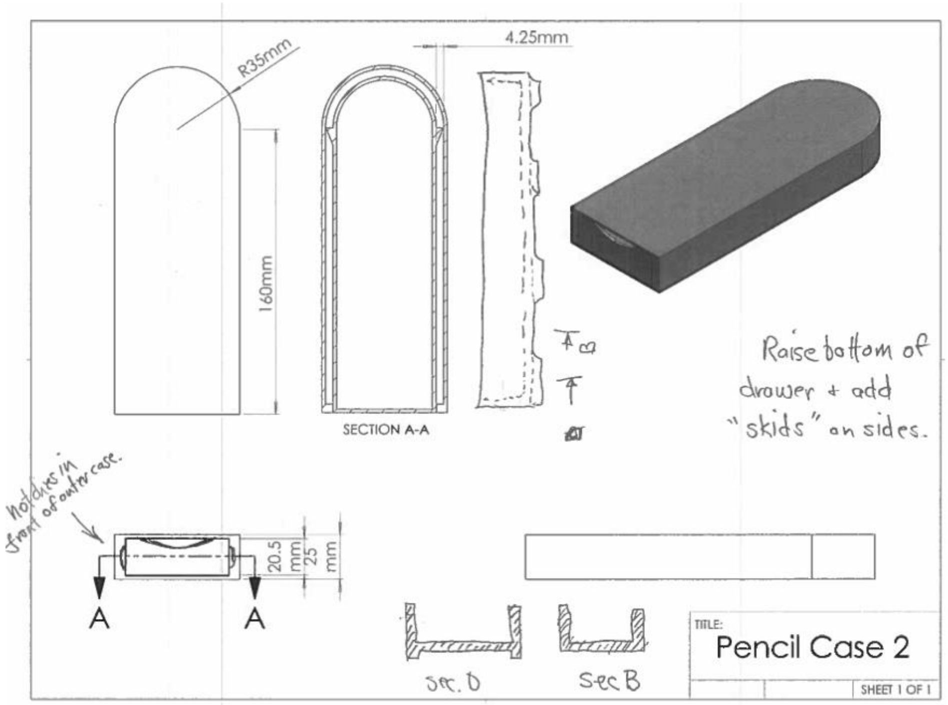

Figure 16: High Quality Pencil Case. Design Material: 1. Support Material: 0. Number of Parts: 1. Functionality: 1. Strength of Print: -1.

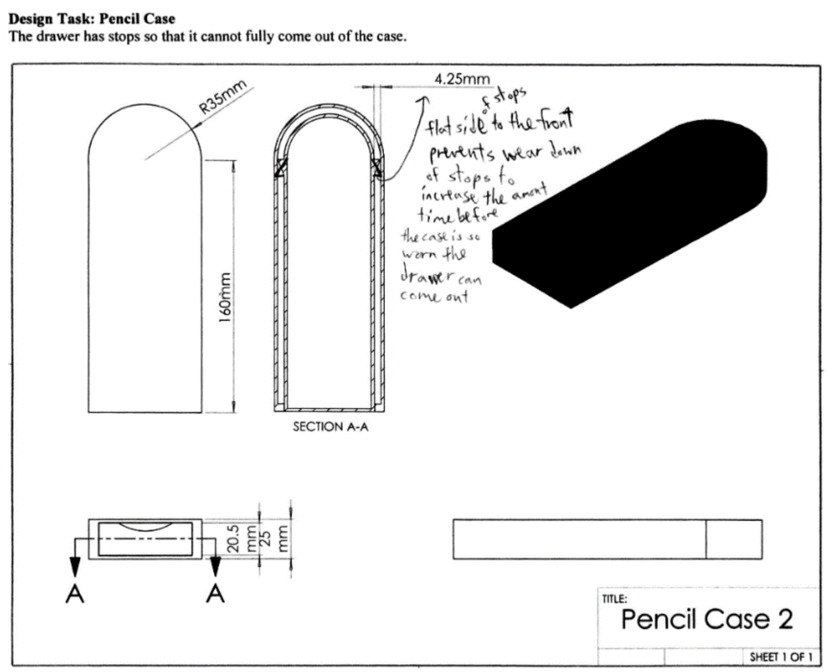

Figure 17: Low Quality Pencil Case. Design Material: 0. Support Material: -1. Number of Parts: 1. Functionality: 0. Strength of Print: -1.

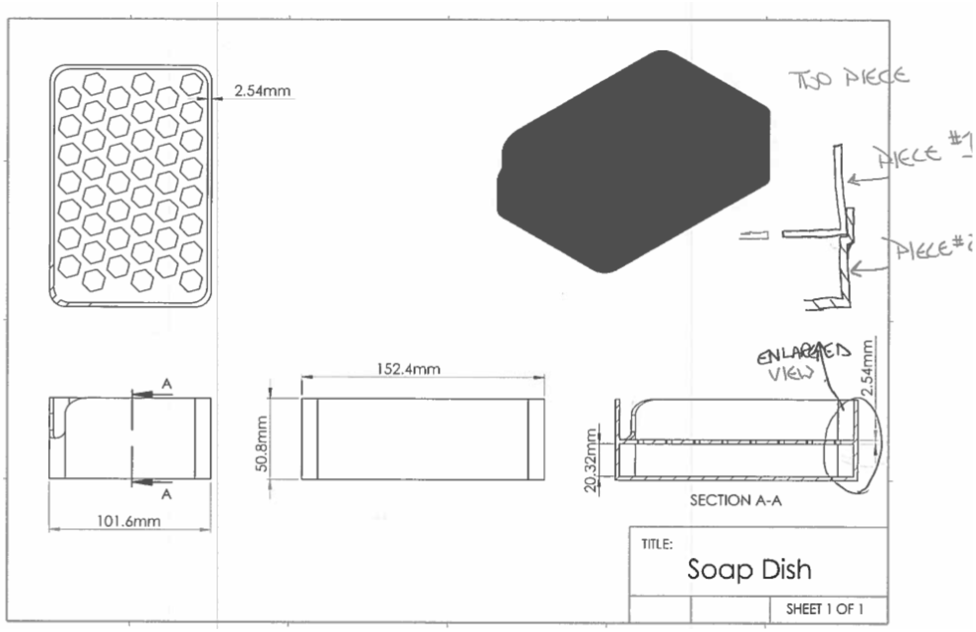

Figure 18: High Quality Soap Dish. Design Material: 0. Support Material: 1. Number of Parts: 0. Functionality: 1. Strength of Print: 1.

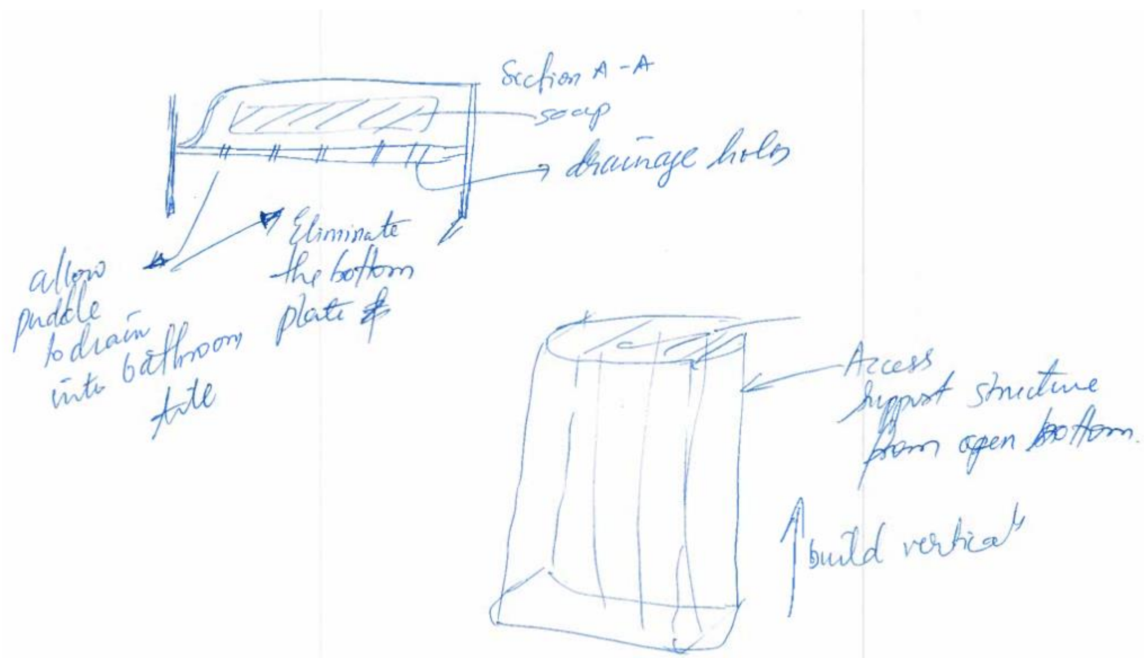

Figure 19: Low Quality Soap Dish. Design Material: 1. Support Material: -1. Number of Parts: 1. Functionality: 0. Strength of Print: -1.

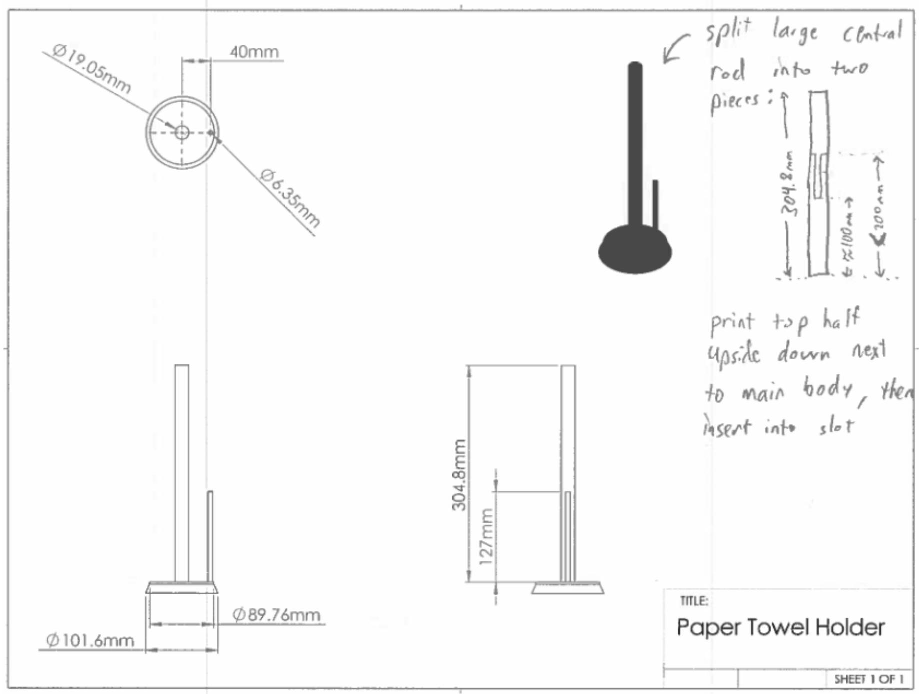

Figure 20: High Quality Paper Towel Holder. Design Material: 0. Support Material: 0. Number of Parts: 1. Functionality: 1. Strength of Print: -1.

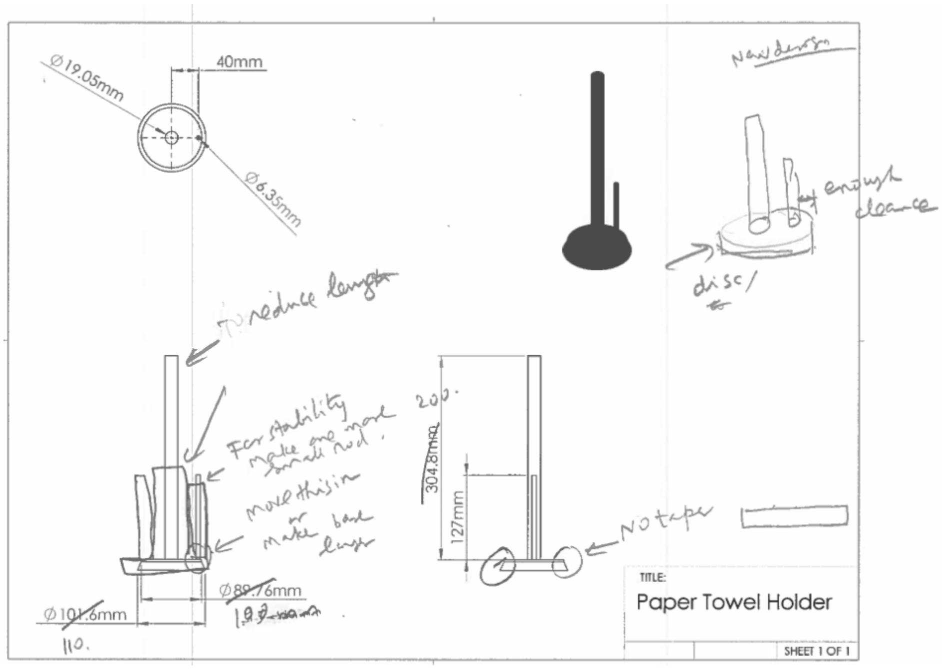

Figure 21: Low Quality Paper Towel Holder. Design Material: 1. Support Material: 0. Number of Parts: 1. Functionality: -1. Strength of Print: -1.

APPENDIX H: SPSS OUTPUT

Table 7: SPSS output from ANOVA of Presentation Effect on Quality and Novelty in Expert Study

Univariate Tests

Source	Measure		Type III Sum of Squares	df	Mean Square	F	Sig.
Presentation	Quality	Sphericity Assumed	.287	3	.096	.922	.435
		Greenhouse-Geisser	.287	2.544	.113	.922	.423
		Huynh-Feldt	.287	2.856	.100	.922	.431
		Lower-bound	.287	1.000	.287	.922	.346
	Novelty	Sphericity Assumed	.047	3	.016	.639	.592
		Greenhouse-Geisser	.047	2.694	.017	.639	.576
		Huynh-Feldt	.047	3.000	.016	.639	.592
		Lower-bound	.047	1.000	.047	.639	.432
Error(Presentation)	Quality	Sphericity Assumed	7.772	75	.104		
		Greenhouse-Geisser	7.772	63.600	.122		
		Huynh-Feldt	7.772	71.411	.109		
		Lower-bound	7.772	25.000	.311		
	Novelty	Sphericity Assumed	1.842	75	.025		
		Greenhouse-Geisser	1.842	67.348	.027		
		Huynh-Feldt	1.842	75.000	.025		
		Lower-bound	1.842	25.000	.074		

Table 8.1, 8.2 and 8.3: SPSS output from Kruskal-Wallis Test and pairwise S-N-K test of Presentation Effect on Rule Understanding in Expert Study

Kruskal-Wallis Test

Ranks

	Presentation	N	Mean Rank
Understanding	1	26	35.90
	2	26	55.62
	3	25	53.54
	4	25	61.40
	Total	102	

Test Statistics[a,b]

	Understanding
Chi-Square	11.471
df	3
Asymp. Sig.	.009

a. Kruskal Wallis Test

b. Grouping Variable: Presentation

Understanding

Student-Newman-Keuls[a,b]

Presentation	N	Subset for alpha = 0.05	
		1	2
1	26	3.12	
3	25		3.80
2	26		3.88
4	25		4.08
Sig.		1.000	.583

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 25.490.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Table 9.1 and 9.2: SPSS output from ANOVA of Presentation Effect on Quality in Novice Study

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	46.312	50.218	.000
Presentation	3	39.243	1.082	.368

a. Dependent Variable: Quality.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.190929	.059858	42.641	3.190	.003	.070185	.311674
[Presentation=Example]	.043553	.075642	49.198	.576	.567	-.108440	.195546
[Presentation=Illustration]	.037800	.077736	37.516	.486	.630	-.119635	.195236
[Presentation=Printed Part]	.128450	.074559	51.817	1.723	.091	-.021176	.278076
[Presentation=Text only]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Quality.

b. This parameter is set to zero because it is redundant.

Table 10.1 and 10.2: SPSS output from ANOVA of Presentation Effect on Novelty in Novice Study

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	49.654	1107.233	.000
Presentation	3	41.055	.007	.999

a. Dependent Variable: Novelty.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.433763	.026213	41.963	16.548	.000	.380863	.486664
[Presentation=Example]	-.003122	.031108	47.388	-.100	.920	-.065689	.059445
[Presentation=Illustration]	-.003347	.031796	46.108	-.105	.917	-.067344	.060650
[Presentation=Printed Part]	-.003957	.029350	46.884	-.135	.893	-.063006	.055092
[Presentation=Text only]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Novelty.

b. This parameter is set to zero because it is redundant.

Table 11.1, 11.2 and 11.3: SPSS output from Kruskal-Wallis Test and pairwise S-N-K test of Presentation Effect on Rule Understanding in Novice Study

Kruskal-Wallis Test

Ranks

	Presentation	N	Mean Rank
Understanding	1	56	79.21
	2	56	116.04
	3	56	118.36
	4	56	136.39
	Total	224	

Test Statistics[a,b]

	Understanding
Chi-Square	24.508
df	3
Asymp. Sig.	.000

a. Kruskal Wallis Test

b. Grouping Variable: Presentation

Understanding

Student-Newman-Keuls[a]

		Subset for alpha = 0.05	
Presentation	N	1	2
1	56	2.89	
2	56		3.68
3	56		3.77
4	56		3.98
Sig.		1.000	.380

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 56.000.

Table 12.1 and 12.2: SPSS output from ANOVA of Expertise Effect on Quality

Fixed Effects

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	238.205	127.115	.000
Expertise	1	238.205	1.890	.171

a. Dependent Variable: Quality.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.247805	.028190	238.420	8.791	.000	.192272	.303339
[Expertise=0]	.068823	.050063	238.205	1.375	.171	-.029799	.167445
[Expertise=1]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Quality.

b. This parameter is set to zero because it is redundant.

Table 13.1 and 13.2: SPSS output from ANOVA of Expertise Effect on Novelty

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	225.383	2450.499	.000
Expertise	1	225.383	5.394	.021

a. Dependent Variable: Novelty.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.429761	.010263	226.285	41.877	.000	.409539	.449984
[Expertise=0]	.042310	.018218	225.383	2.322	.021	.006411	.078209
[Expertise=1]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Novelty.

b. This parameter is set to zero because it is redundant.

Table 14.1 and 14.2: SPSS output from Mann-Whitney Test of Expertise Effect on Rule Understanding

Mann-Whitney Test

Ranks

	Expertise	N	Mean Rank	Sum of Ranks
Understanding	0	102	167.36	17070.50
	1	224	161.74	36230.50
	Total	326		

Test Statistics[a]

	Understanding
Mann-Whitney U	11030.500
Wilcoxon W	36230.500
Z	-.515
Asymp. Sig. (2-tailed)	.606

a. Grouping Variable: Expertise

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