

Examining the effect of design for additive manufacturing rule presentation on part redesign quality

Kenton Blane Fillingim , Richard O. Nwaeri , Christiaan J. J. Paredis , David Rosen & Katherine Fu

To cite this article: Kenton Blane Fillingim , Richard O. Nwaeri , Christiaan J. J. Paredis , David Rosen & Katherine Fu (2020): Examining the effect of design for additive manufacturing rule presentation on part redesign quality, *Journal of Engineering Design*, DOI: [10.1080/09544828.2020.1789569](https://doi.org/10.1080/09544828.2020.1789569)

To link to this article: <https://doi.org/10.1080/09544828.2020.1789569>



Published online: 09 Jul 2020.



Submit your article to this journal 

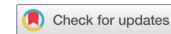


View related articles 



CrossMark

View Crossmark data 



Examining the effect of design for additive manufacturing rule presentation on part redesign quality

Kenton Blane Fillingim^a, Richard O. Nwaeri^a, Christiaan J. J. Paredis^b, David Rosen^a and Katherine Fu^a

^aMechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA; ^bAutomotive Engineering, Clemson University, Greenville, SC, USA

ABSTRACT

The main goal of this research is to understand how design for additive manufacturing (DfAM) rule presentation affects a designer's ability to utilise 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 modelling (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 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.

ARTICLE HISTORY

Received 9 June 2019

Accepted 26 June 2020

KEYWORDS

Heuristics; design; additive manufacturing; quality; novelty; redesign; modality; experts; novices

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 through a digital process to create the part, hence the name additive manufacturing. While these processes are not necessarily new, in recent years, their popularity has expanded rapidly 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 provides designers with guidelines for using additive technology, as well as the opportunity to explore aspects such as unique geometries and material properties that can only be produced through additive manufacturing.

One unique aspect of DfAM is that its recent increase in popularity means that many current industry professionals may not have received formal education in this area. For these professionals, obtaining heuristic knowledge through training may allow them to have DfAM competency without obtaining it in a traditional classroom setting. Although many tools and resources have been developed for training, access is still somewhat limited, and there is a need to understand how AM training can be most efficiently implemented across various environments (Huang et al. 2015). Regardless of the method used for instructing these professionals, one important question as a starting point is how best to display this information. Building upon the work done by Dinar and Rosen (2016), which focused on the formalisation of DfAM guidelines, this study 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. This study will view DfAM as a restrictive process, meaning it provides guidelines for refining designs to meet the restrictions of additive manufacturing technology. The differences between DfAM's restrictive and opportunistic characteristics are discussed in more detail in the following section. 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. Based on the goals stated above, there are 2 major research questions that are addressed by this study:

- (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 applied across the two key groups for which it could be useful.

Literature review

Design for additive manufacturing

In recent years, an increasing number of designers have realised the benefits of concurrent engineering (Eastman 2012). 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 (Kuo, Huang, and Zhang 2001).

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 (Doubrovski, Verlinden, and Geraedts 2011; Thompson et al. 2016). 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 do not have this restriction, as the cost is generally unaffected by the complexity of the design (Hopkinson, Hague, and Dickens 2006). Conversely, factors such as part orientation (Thrimurthulu, Pandey, and Venkata Reddy 2004) and support material optimisation (Strano et al. 2013) are considerations completely unique to additive manufacturing, which if ignored can lead to parts with issues such as reduced strength, loss of functionality, or even complete failure during the fabrication process. 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 (Laverne et al. 2015).

Opportunistic DfAM refers to any DfAM method that aims to utilise 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 (Tibbits 2014). One of the best examples of these opportunistic DfAM methods is topology optimisation, in which the material in a part is redistributed to optimise 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 (Langelaar 2016), as there is still much work to be done before it fully captures all of the aspects of a 3D printed part. However, much progress has been made to improve topology optimisation for manufacturability (Leary et al. 2014)(Leary et al. 2014), considering aspects such as minimal support material that 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 do not 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 study, 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 (Ponche et al. 2012), 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 explore a larger design space, which can lead to higher innovation, rather than simply building upon parts made for other processes. One way to get the innovative aspect of DfAM into industry has been to computerise the process by utilising optimisation techniques to create CAD tools that could potentially improve designs (Strano et al. 2013; Rosen 2007); 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 these tools do become the standard in industry, a simple method to aid designers in transforming their design into AM-ready parts is necessary, and this is where heuristics come into play.

The design rules presented in this paper are imagined to be implemented through the embodiment and detail design phases, as described by Pahl et al. (2007). Embodiment design begins after the core solution concept has been chosen, and the designer must integrate technical and economic constraints to further develop that concept. In detail design, dimensions and surface properties are finalised and prepared for production, especially through detailed documents, drawings, and parts lists. Kumke, Watschke, and Vietor (2016) agree with this in their modified design process for additive manufacturing, adding AM-conformal design rules and guidelines into the embodiment and detail design phases. For this study, it is assumed that the designer has not been highly involved with printing processes past this point in the design process, as we are introducing design rules to those new to the DfAM process. However, this is sometimes not the case, and designers that are more interactive with production processes may have different perspectives on implementing DfAM heuristics into their designs. Additionally, this work assumes that the designer's role ends at the 3D model, as they are not asked to participate in slicing or the actual printing of the redesigned parts.

Heuristics

Heuristics are often colloquially referred to as guidelines or rules-of-thumb. Fu, Yang, and Wood (2016) 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 (Blösch-Paidosh and Shea 2017). As a result, much of the research into DfAM heuristics has focused on specific processes or machines (Urbanic and Hedrick 2016; Kranz, Herzog, and Emmelmann 2015). 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 (2017) created a list of 29 general heuristics based on their analysis of hundreds of existing AM designs. Similarly, Adam and Zimmer (2014) found several heuristics that are applicable to multiple processes when deriving heuristics for laser melting, laser sintering and fused deposition modelling individually. Generic heuristics such as these are valuable due to 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 (Gigerenzer 2008). As a result, despite these concerns, research has continued looking into the potential benefits heuristic use provides. Yilmaz, Seifert, and Gonzalez (2010) 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 (2019) showed that by exposing novice designers to the general DfAM heuristics they previously generated (2017), 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 (Reinwein 2012), one common explanation is based on the Cognitive Load Theory proposed by Sweller, Van Merriënboer, and Paas (1998); this theory suggests that by utilising 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 utilising both visual and auditory representations for learning (Ginns 2005), specific visual modalities have also been studied such as animations and non-verbal gestures (Atkinson 2002). 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 (Goel 1997). 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 (Markman et al. 2009), the ideal way to communicate these analogies should be found (Chan et al. 2011). 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. 2011; Toh and Miller 2014; Viswanathan and Linsey 2013; Barnawal et al. 2017). However, 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 allows for parts to be manufactured relatively rapid and cheap to be implemented into instructional material. It also provides an avenue to visualise aspects that traditional manufacturing cannot offer, such as parts made of multiple materials in one print, parts printed within other parts, or parts embedded with sensors or electronics. 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. 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 (Dorst and Reymen 2004), 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 (Cross 2004).

While the general concept of an expert is not new, the behaviour 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 (2004) 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 (2001) 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 study 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.

Based on this literature review, there are a few hypotheses that can be made in relation 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 (Viswanathan and Linsey 2013), 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) (Chan et al. 2011). 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 (Barnawal et al. 2017). Finally, it was found that there was subjective preference of the 3D modality (Barnawal et al. 2017), 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 (Cross 2004). 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.

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 (Kranz, Herzog, and Emmelmann 2015) based on how suitable they were to be applied to a design problem that could be completed within the anticipated time (roughly 10 min). 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

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

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.

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.

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

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

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

Each rule as presented in all four modalities can be found in Appendix 1. Each associated design problem can be found in Appendix 2. Each design rule, associated design problem, and mode of presentation occurs only once per participant. A two-level randomisation process was used to assemble experimental packets. Randomisation was performed using an online random number generator. The first level randomised the order in which each design rule was presented to the participant. The second level randomised the mode of presentation of the design rule. Each mode of presentation was used only once for each participant. In other words, participants received every presentation mode and design rule once during the experiment. The difference lies in the order in which they were received, and the pairings between design rule and modality. An example experiment packet is shown in Table 2. Design problems were placed in individual envelopes labelled Phase A-D so participants did not attempt problems out of order and were only looking at one problem at a time. Additionally, each printed part was placed in a sealed bag labelled with the corresponding phase. Participants were not allowed to open the bag until the appropriate phase, and they were asked to put the printed parts back into the sealed bag before moving on to additional phases.

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 3. 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. Although these participants 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. 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 4. Researchers alerted participants when there were 5 min 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

min to complete the provided survey. A copy of this survey can be found in Appendix 5. 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. Sample solutions for each design problem can be found in Appendix 6. The decision to focus on quality and novelty as the criteria for the metrics was based on the framework created by Shah, Kulkarni, and Vargas-Hernandez (2000); although, the specifics of both metrics were created specifically for this study. Solution quality is necessary for determining the designer's ability to adhere to the restrictions of manufacturing without negatively impacting the value of the design. Novelty is beneficial for understanding the designer's ability to adhere to the restrictions of manufacturing with minimum impact on innovation and creativity performed in the opportunistic phase of DfAM. While this study focuses on the restrictive aspect of DfAM, a design rule which can preserve a designer's product quality and novelty should be considered more valuable to the design process. 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. Each criterion, described below, was judged on a three-point scale (-1, 0, 1).

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. CAD models were not needed to determine design material or support material, as the researchers could infer from the redesigns whether more, less, or the same amount of material would be necessary. For example, if a participant eliminated a portion of the soap dish wall for easier access to support material, it can be concluded that this design requires less design material but equal support material as the baseline design.

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. Three of the four designs (juicer, soap dish, and pencil case) could be adequately modified without adding any additional parts to the solution. Only the paper towel holder required a solution with at least two parts.

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 negative scores. Any diagonally oriented designs were given neutral scores. The design flaw created for each design prompt, such as the overhang present in the juicer, implies that the design will be printed in the orientation shown in the drawing. If the participant did not indicate a print orientation, it was assumed that the orientation did not change from its original position.

Two researchers independently examined and rated the quality of 25% of the participants. 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 cannot be considered a good design; thus, it is reasonable for the functionality to be weighted the same as all other categories combined.

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 normalising the scores to a score out of 1. This novelty calculation is based on the method suggested by Shah, Kulkarni, and Vargas-Hernandez (2000).

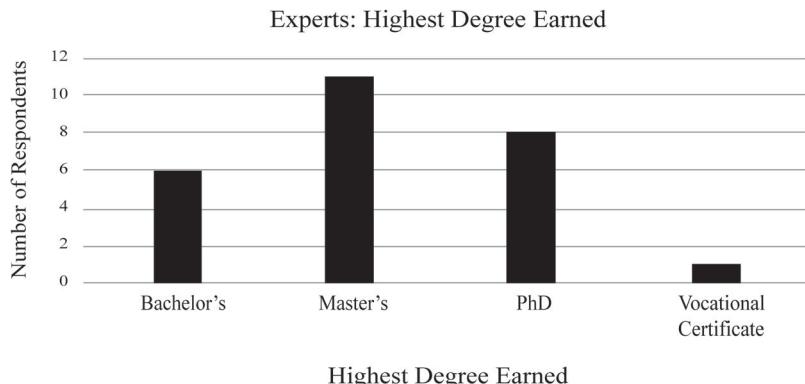
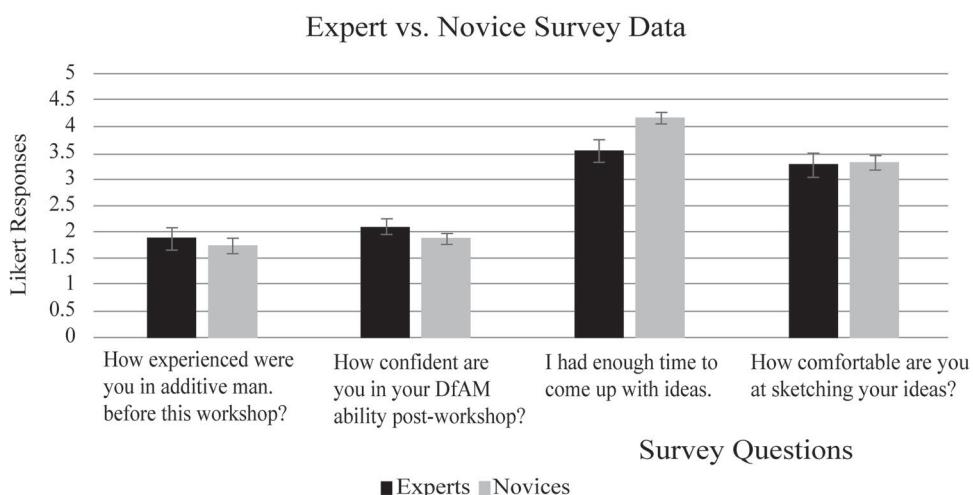
Results

Demographics

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, 20

Table 3. Expert demographic data for experience.

	Current Company (Yrs)	Design Exp. (Yrs)	Engineering Exp (Yrs)
Average	9.8269	9.840	15
Min	1	0	0
Max	28	36	40
St. Dev.	7.333	9.697	10.421

**Figure 1.** Distribution of highest degree earned within expert study.**Figure 2.** Survey responses of experts and novices. Error bars show ± 1 SD.

participants had a background in mechanical engineering, 2 in material science, 4 in aerospace engineering, and 6 in other fields. Twenty-three participants worked as some form of engineer at the company. Additional information of experience, education and background within the group can be found in Table 3 and Figures 1 and 2.

The novice study consisted of 56 participants, of which 22 were female and 34 were male. No participants were excluded from the novice study. More information about the novice study participants can be found in Figure 2. 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.

Data analysis

To analyse 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 utilising 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 analyse 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 analyse 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.

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 3) 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 4) for both experts and novices ($F(3,75) = 0.639, p = 0.592$ and $F(3,41.1) = 0.007, p = 0.999$, respectively).

The analysis of the effect of rule presentation modality on rated ease of understanding showed there was a significant effect of presentation (Figure 5) 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 analysing 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.

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 rated ease of understanding ($U = 11,030.5, p = 0.606$). There was, however, a significant effect of expertise on novelty, with experts being shown

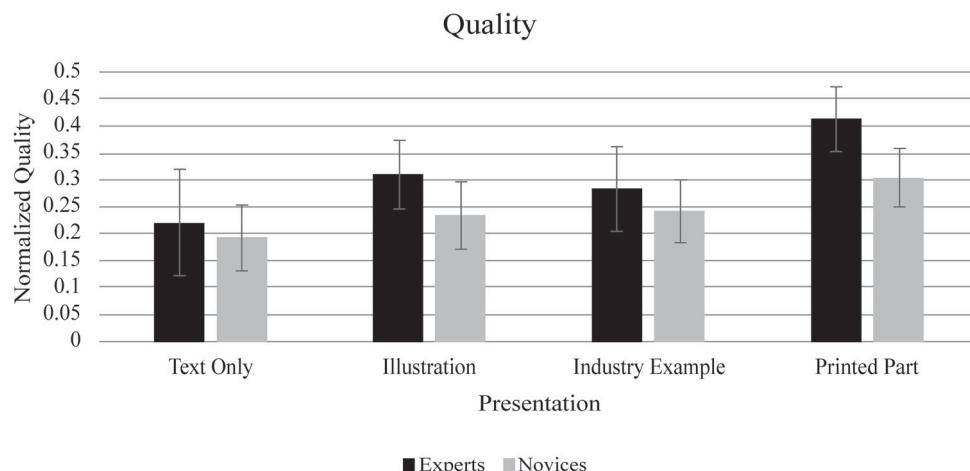


Figure 3. Quality of redesign solutions of experts and novices. Error bars show ± 1 SD.

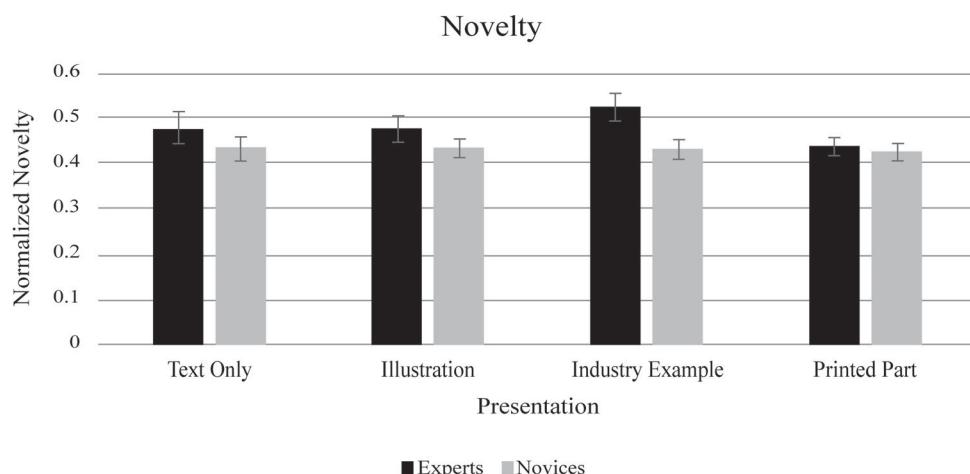


Figure 4. Novelty of redesign solutions of experts and novices. Error bars show ± 1 SD.

to have higher novelty scores than novices ($F(1,225.4) = 5.394, p < 0.05$), with an effect size of 0.318.

Discussion

Expert study

Results show that the experts showed no difference in their quality or novelty scores based on the rule presentation modality they were exposed to. Additional analysis was performed to see if the order of the modality or tasks had any impact on the quality or novelty scores, but this was insignificant as well. 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. The lack of significance for quality was

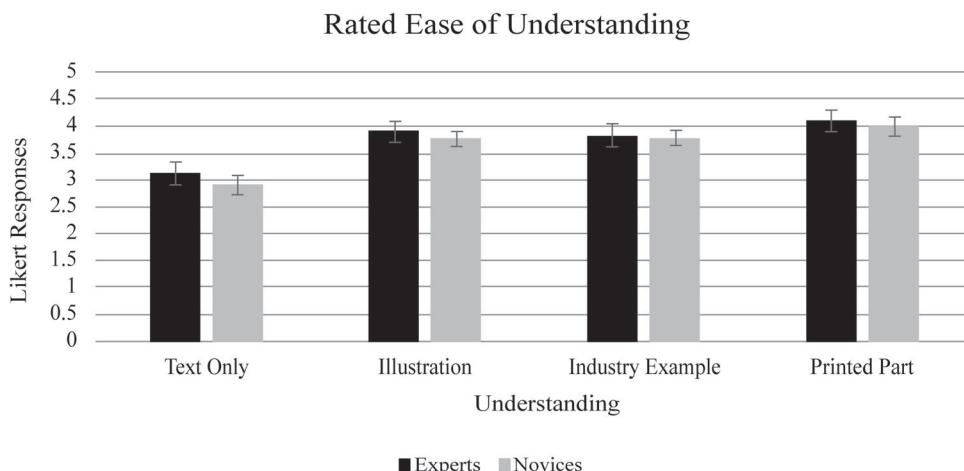


Figure 5. Rated understanding of design rules of experts and novices. Error bars show ± 1 SD.

interesting does 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 may be 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, which believed that the printed part modality would have the lowest novelty scores due to fixation on

the examples, while the illustrations and industry examples would produce the highest novelty redesigns. This does not seem to match prior expectations, but 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 were 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, several of the text-based 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. Perhaps for future studies, one way to see more novel results that are realistic would be to ask participants to generate multiple ideas for each design rule. With multiple redesigns, research suggests the likelihood of a participant producing at least one high-novelty, feasible idea naturally increases (Tsenn et al. 2014). 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). 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 internalised 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

The novice study yielded 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. Similar to the expert study, order in which modality or tasks were received did not lead to any significant difference in quality or novelty. 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.

Experts and novices did not significantly differ from each other in quality, which means hypothesis 2b (H2b) was not supported by the data. 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, as shown in Figure 2. Given the uniqueness of additive manufacturing rules, 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 the primary area in which experts and novices differed, with experts demonstrating significantly higher novelty scores than novices, based on the average novelty score across all design tasks. 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 the same for experts and novices. This means although the expert study showed 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 (Viswanathan and Linsey 2013), 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 (Viswanathan and Linsey 2011), it is still difficult to say with certainty whether this effect plays a role in this context without additional research.

Contributions

Ultimately, this work has contributed to the literature on design heuristics and design for additive manufacturing in a number of ways. First, by studying both design professionals from industry and design students, 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 formalised instruction is often seen even in an

industry setting. Along similar lines, this study 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.

From a heuristics perspective, the study could be the foundation for studying how effectively designers can retain and apply heuristics formed by others that were not yet engrained into their own design processes. It also explores how to best present heuristics to designers, which can be applied across all design domains. 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. Outside of DfAM, this work can extend to training in all areas of design where each of the four modalities of heuristics may be applicable for presentation. As previously stated, designers should prefer the ability to implement a heuristic that allows a design to abide by the restrictions of manufacturing, while also preserving both its quality and novelty. To this end, this work could build upon design literature seeking to understand the value of heuristics to the design process.

Limitations and 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, the sample of experts for the study was not as diverse as desired, as no females were included in the study. While the novice study sample 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, as previously stated, there is a large variance in levels of experience for the expert sample. 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 (Crismond 2001), 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. 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 cannot 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.



There are limitations of this study that stem from the metrics used as well, which could be improved in future studies. While the quality rubric addresses many aspects that add value to the design, it is possible for scenarios to exist that the rubric does not anticipate, such as instances where support material may benefit the design in question. Additionally, receiving self-reported ease of understanding measures in the survey was the most direct way of determining one's attitude towards the rule presentation modalities, but 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 have 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.

Novelty was found to be unaffected by modality, but there was a significance difference between the experts and novices. Understanding why modality does not contribute a difference could be discovered in future studies, with modifications in design problems, time per problem, and design rules presented. Design problems and rules may have been too simple for a diverse set of solutions, so an extension of this study could provide a new set of design rules and problems labelled with various levels of difficulty, which could then determine if modality matters for problems of higher difficulty. A similar extension could vary levels of time allotted per participant to see if some modalities lead to higher novelty, given an adequate amount of time to ideate.

Conclusions

Ultimately, all of the initial research objectives 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. 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 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 study. 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 there was no effect of expertise on quality of redesigns or ease of understanding. However, 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.

Acknowledgments

The research presented in this paper was supported in part by the National Science Foundation under Award CMMI-1645316. The United States Government retains, and by accepting the article for publication, the publisher acknowledges that the United States Government retains, a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes. We would like to sincerely thank Carolyn Seepersad for her expertise and assistance in developing the short course, study methodology and design prompts. We would also like to thank Siemens Energy, Inc. employees and management for their participation in and support of this research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The research presented in this paper was supported in part by the National Science Foundation under award [CMMI-1645316].

References

Adam, Guido A. O., and Detmar Zimmer. 2014. "Design for Additive Manufacturing – Element Transitions and Aggregated Structures." *CIRP Journal of Manufacturing Science and Technology* 7 (1): 20–28.

Atkinson, Robert K. 2002. "Optimizing Learning from Examples Using Animated Pedagogical Agents." *Journal of Educational Psychology* 94 (2): 416.

Barnawal, Prashant, Michael C. Dorneich, Matthew C. Frank, and Frank Peters. 2017. "Evaluation of Design Feedback Modality in Design for Manufacturability." *Journal of Mechanical Design* 139 (9): 094503–094503-5. [doi:10.1115/1.4037109](https://doi.org/10.1115/1.4037109).

Blösch-Paidosh, Alexandra, and Kristina Shea. 2017. "Design Heuristics for Additive Manufacturing." 21st International Conference on Engineering Design (ICED 17), Vancouver, BC, August 21–25.

Blösch-Paidosh, Alexandra, and Kristina Shea. 2019. "Design Heuristics for Additive Manufacturing Validated Through a User Study." *Journal of Mechanical Design* 141 (4): 041101–041101-8. doi:10.1115/1.4041051.

Chan, Joel, Katherine Fu, Christian Schunn, Jonathan Cagan, Kristin Wood, and Kenneth Kotovsky. 2011. "On the Benefits and Pitfalls of Analogies for Innovative Design: Ideation Performance Based on Analogical Distance, Commonness, and Modality of Examples." *Journal of Mechanical Design* 133 (8): 081004–081004-11. doi:10.1115/1.4004396.

Crismond, David. 2001. "Learning and Using Science Ideas When Doing Investigate-and-Redesign Tasks: A Study of Naive, Novice, and Expert Designers Doing Constrained and Scaffolded Design Work." *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching* 38 (7): 791–820.

Cross, Nigel. 2004. "Expertise in Design: An Overview." *Design Studies* 25 (5): 427–441.

Dinar, Mahmoud, and David W. Rosen. 2016. "A Design for Additive Manufacturing Ontology." (50084): V01BT02A032. doi:10.1115/DETC2016-60196.

Dorst, Kees, and I. M. M. J. Reymen. 2004. "Levels of Expertise in Design Education." DS 33: Proceedings of E&PDE 2004, the 7th International Conference on Engineering and Product Design Education, Delft, September 2–3.

Doubravski, Zjenja, Jouke C. Verlinden, and Jo M. P. Geraedts. 2011. "Optimal Design for Additive Manufacturing: Opportunities and Challenges." (54860): 635–646. doi:10.1115/DETC2011-48131.

Eastman, Charles M. 2012. *Design for X: Concurrent Engineering Imperatives*. Dordrecht, Netherlands: Springer Science & Business Media.

Fu, Katherine K., Maria C. Yang, and Kristin L. Wood. 2016. "Design Principles: Literature Review, Analysis, and Future Directions." *Journal of Mechanical Design* 138 (10): 101103–101103-13. doi:10.1115/1.4034105.

Gigerenzer, Gerd. 2008. "Why Heuristics Work." *Perspectives on Psychological Science* 3 (1): 20–29. doi:10.1111/j.1745-6916.2008.00058.x.

Ginns, Paul. 2005. "Meta-Analysis of the Modality Effect." *Learning and Instruction* 15 (4): 313–331.

Goel, Ashok K. 1997. "Design, Analogy, and Creativity." *IEEE Expert* 12 (3): 62–70.

Hopkinson, Neil, Richard Hague, and Philip Dickens. 2006. *Rapid Manufacturing: An Industrial Revolution for the Digital Age*. West Sussex, England: John Wiley & Sons.

Huang, Yong, Ming C. Leu, Jyoti Mazumder, and Alkan Donmez. 2015. "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations." *Journal of Manufacturing Science and Engineering* 137: 1–10.

Kranz, J., D. Herzog, and C. Emmelmann. 2015. "Design Guidelines for Laser Additive Manufacturing of Lightweight Structures in TiAl6V4." *Journal of Laser Applications* 27 (S1): S14001. doi:10.2351/1.4885235.

Kumke, Martin, Hagen Watschke, and Thomas Vietor. 2016. "A New Methodological Framework for Design for Additive Manufacturing." *Virtual and Physical Prototyping* 11 (1): 3–19.

Kuo, Tsai-C., Samuel H. Huang, and Hong-C. Zhang. 2001. "Design for Manufacture and Design for 'X': Concepts, Applications, and Perspectives." *Computers & Industrial Engineering* 41 (3): 241–260.

Langelaar, Matthijs. 2016. "Topology Optimization of 3D Self-Supporting Structures for Additive Manufacturing." *Additive Manufacturing* 12: 60–70.

Laverne, Floriane, Frédéric Segonds, Nabil Anwer, and Marc Le Coq. 2015. "Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study." *Journal of Mechanical Design* 137 (12): 121701–121701-8. doi:10.1115/1.4031589.

Leary, Martin, Luigi Merli, Federico Torti, Maciej Mazur, and Milan Brandt. 2014. "Optimal Topology for Additive Manufacture: A Method for Enabling Additive Manufacture of Support-Free Optimal Structures." *Materials and Design* 63: 678–690.

Markman, A. B., K. L. Wood, J. S. Linsey, J. T. Murphy, and Jeffrey Laux. 2009. "Supporting Innovation by Promoting Analogical Reasoning." *Tools for Innovation* 1 (9): 85–104.

Pahl, G., W. Beitz, J. Feldhusen, and K. H. Grote. 2007. *Engineering Design: A Systematic Approach*. 3rd ed. London: Springer.

Ponche, Rémi, Jean-Yves Hascoët, Olivier Kerbrat, and Pascal Mognol. 2012. "A New Global Approach to Design for Additive Manufacturing: A Method to Obtain a Design that Meets Specifications While

Optimizing a Given Additive Manufacturing Process is Presented in This Paper." *Virtual and Physical Prototyping* 7 (2): 93–105.

Reinwein, Joachim. 2012. "Does the Modality Effect Exist? And if So, Which Modality Effect?" *Journal of Psycholinguistic Research* 41 (1): 1–32. doi:10.1007/s10936-011-9180-4.

Rosen, David W. 2007. "Design for Additive Manufacturing: A Method to Explore Unexplored Regions of the Design Space." Eighteenth Annual Solid Freeform Fabrication Symposium, Austin, TX, August 6–8.

Shah, Jami J, Santosh V Kulkarni, and Noe Vargas-Hernandez. 2000. "Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments." *Journal of Mechanical Design* 122 (4): 377–384.

Strano, G., L. Hao, R. M. Everson, and K. E. Evans. 2013. "A New Approach to the Design and Optimisation of Support Structures in Additive Manufacturing." *The International Journal of Advanced Manufacturing Technology* 66 (9): 1247–1254. doi:10.1007/s00170-012-4403-x.

Sweller, John, Jeroen J. G. Van Merriënboer, and Fred G. W. C. Paas. 1998. "Cognitive Architecture and Instructional Design." *Educational Psychology Review* 10 (3): 251–296.

Thompson, Mary Kathryn, Giovanni Moroni, Tom Vaneker, Georges Fadel, R. Ian Campbell, Ian Gibson, Alain Bernard, Joachim Schulz, Patricia Graf, and Bhrigu Ahuja. 2016. "Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints." *CIRP Annals* 65 (2): 737–760.

Thrimurthulu, K. P. P. M., Pulak M Pandey, and N. Venkata Reddy. 2004. "Optimum Part Deposition Orientation in Fused Deposition Modeling." *International Journal of Machine Tools and Manufacture* 44 (6): 585–594.

Tibbits, Skylar. 2014. "4D Printing: Multi-Material Shape Change." *Architectural Design* 84 (1): 116–121. doi:10.1002/ad.1710.

Toh, Christine A., and Scarlett R. Miller. 2014. "The Impact of Example Modality and Physical Interactions on Design Creativity." *Journal of Mechanical Design* 136 (9): 091004–091004-8. doi:10.1115/1.4027639.

Tsenn, Joanna, Olufunmilola Atilola, Daniel A McAdams, and Julie S Linsey. 2014. "The Effects of Time and Incubation on Design Concept Generation." *Design Studies* 35 (5): 500–526.

Urbanic, R. J., and R. Hedrick. 2016. "Fused Deposition Modeling Design Rules for Building Large, Complex Components." *Computer-Aided Design and Applications* 13 (3): 348–368.

Viswanathan, Vimal, and Julie Linsey. 2011. "Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost." (54860): 119–130. doi:10.1115/DETC2011-47862.

Viswanathan, Vimal, and Julie Linsey. 2013. "Examining Design Fixation in Engineering Idea Generation: The Role of Example Modality." *International Journal of Design Creativity and Innovation* 1 (2): 109–129.

Yilmaz, Seda, Colleen M. Seifert, and R. Gonzalez. 2010. "Cognitive Heuristics in Design: Instructional Strategies to Increase Creativity in Idea Generation." *AI EDAM* 24 (3): 335–355.



Appendices

Appendix 1. Rule presentations

Table A1. 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 minimise 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 A2. Rules in illustration format.

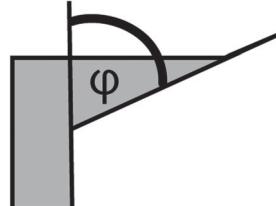
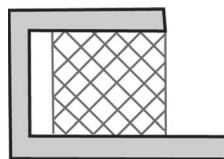
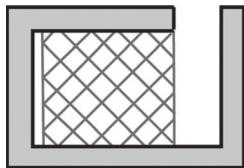
Rule	Justification	Favourable	Unfavourable
If there is an overhang on the part, ensure that the angle is smaller than (Spec. 8)	For horizontal, or near horizontal overhangs, supports will be needed if the overhang is longer than (Spec. 9). As a result, if you are trying to avoid the use of supports, 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 minimise 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.		

Table A2. Rules in illustration format.

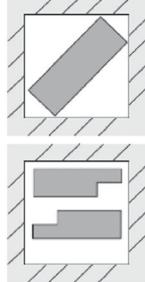
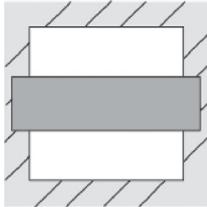
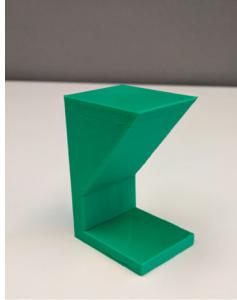
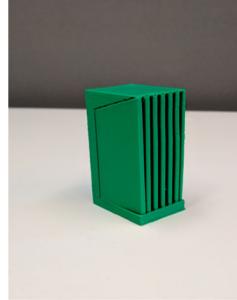
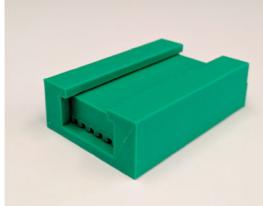
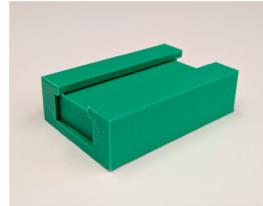
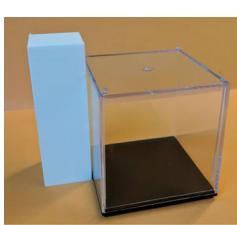
Rule	Justification	Favourable	Unfavourable
If the part is larger than the build area in one dimension, either reorient it, or split the part into two.	Depending on how large the printer you have access to is, you may be limited in how large you can make your part. As a result, it can be useful to turn it into two parts and add fasteners to join them after printing.		

Table A3. Rules in industry example format.

Rule	Justification	Favourable	Unfavourable
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 minimise 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 A4.** Rules in printed part format.

Rule	Justification	Favourable	Unfavourable
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 minimise 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 2. Design problems

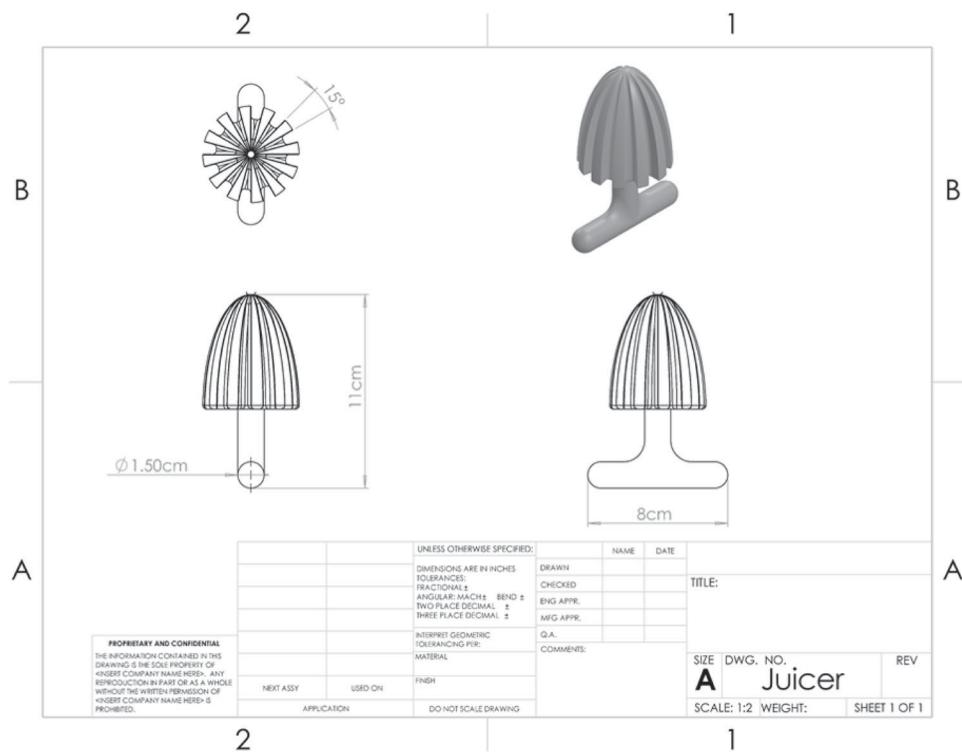


Figure A1. Overhang problem. 'Handheld juicer to extract juice from small citrus fruits.'

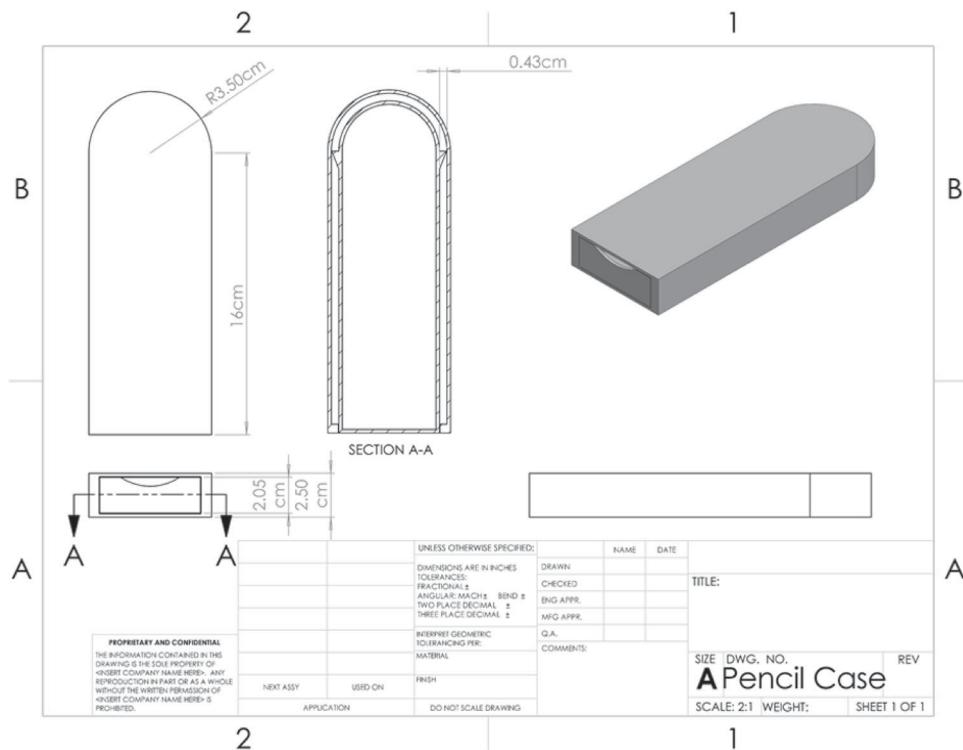
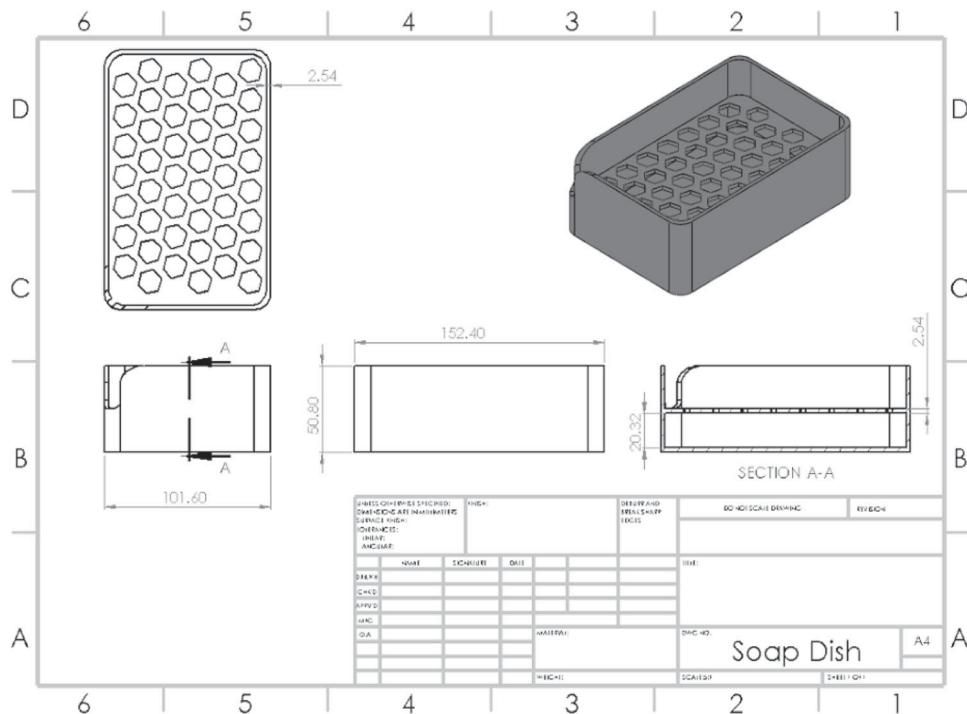


Figure A2. Prismatic joint problem. ‘Pencil case: The drawer is blocked off so that it cannot fully come out of the case.’



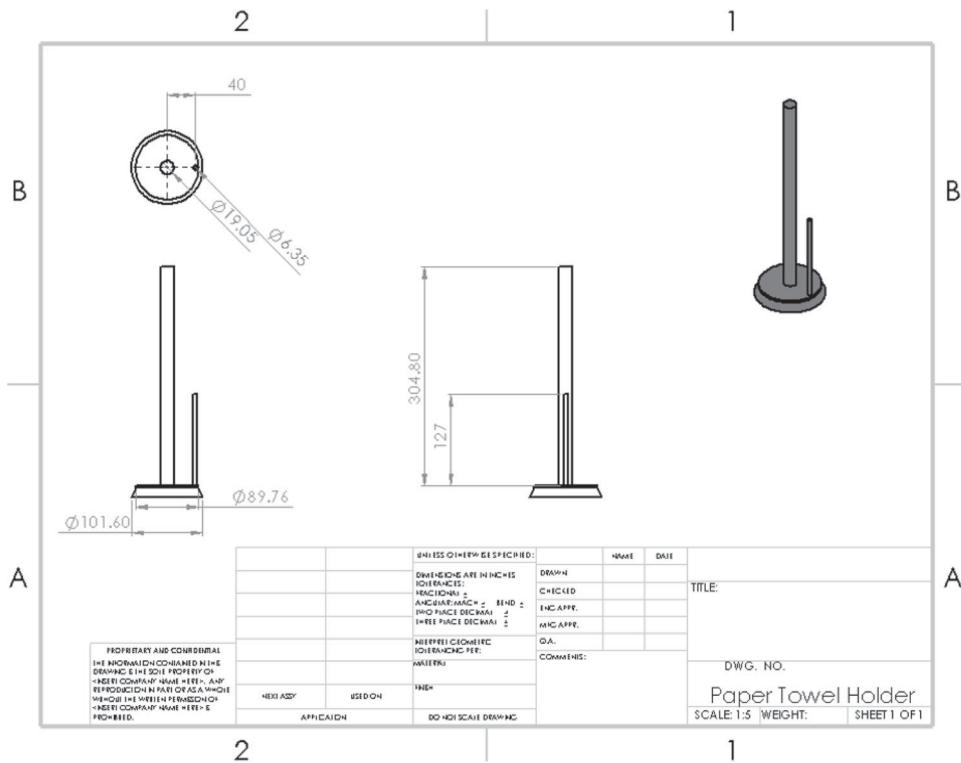


Figure A4. Part size problem. 'Paper towel holder: the paper towel roll fits over the main large rod, with the smaller rod used for removing individual towels.'

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

Appendix 5. 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
- 23–26
- 27–30
- 31–35
- 36–40
- 41–50
- 51–60
- 61–70
- 71–80
- 80+

What is your gender?

- Male
- Female
- 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 do 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	3	4	Completely Inexperienced
<input type="radio"/>				

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	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Design Problem 2	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Design Problem 3	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Design Problem 4	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

How easy were the following rules to understand?

	Extremely Easy	Somewhat Easy	Neither Easy nor Difficult	Somewhat Difficult	Extremely Difficult
Rule 1 (Overhangs)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Rule 2 (Prismatic Joints)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Rule 3 (Accessible Support Structures)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Rule 4 (Part Size)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Overall, how effective do you think this workshop was?

- Very Ineffective
- Somewhat Ineffective
- Neither Effective nor Ineffective
- Somewhat Effective
- Very Effective

Appendix 6. Sample redesigns

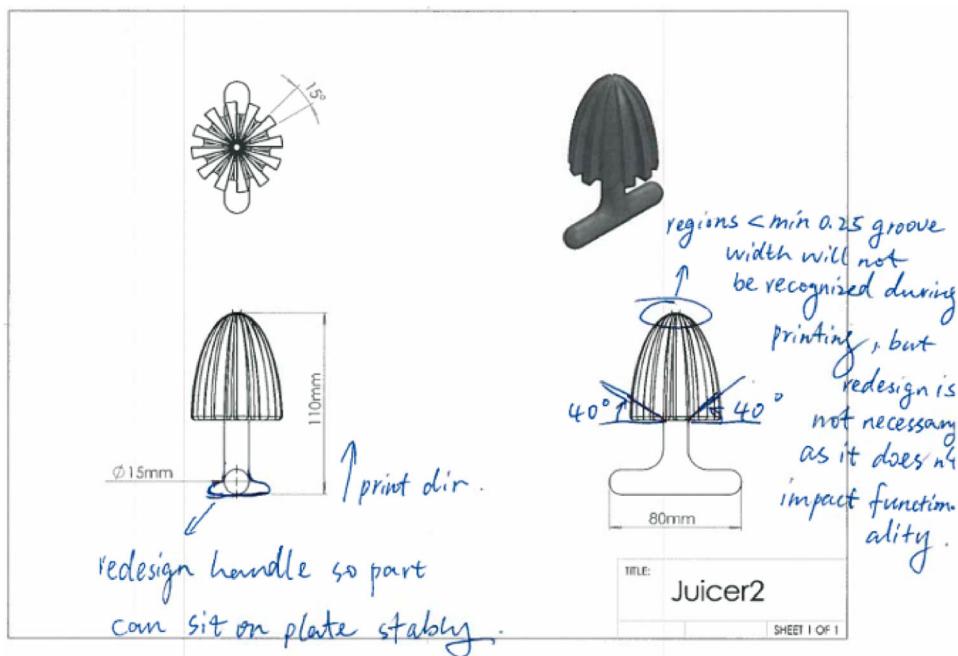


Figure A5. Sample overhang problem redesign (colour online).

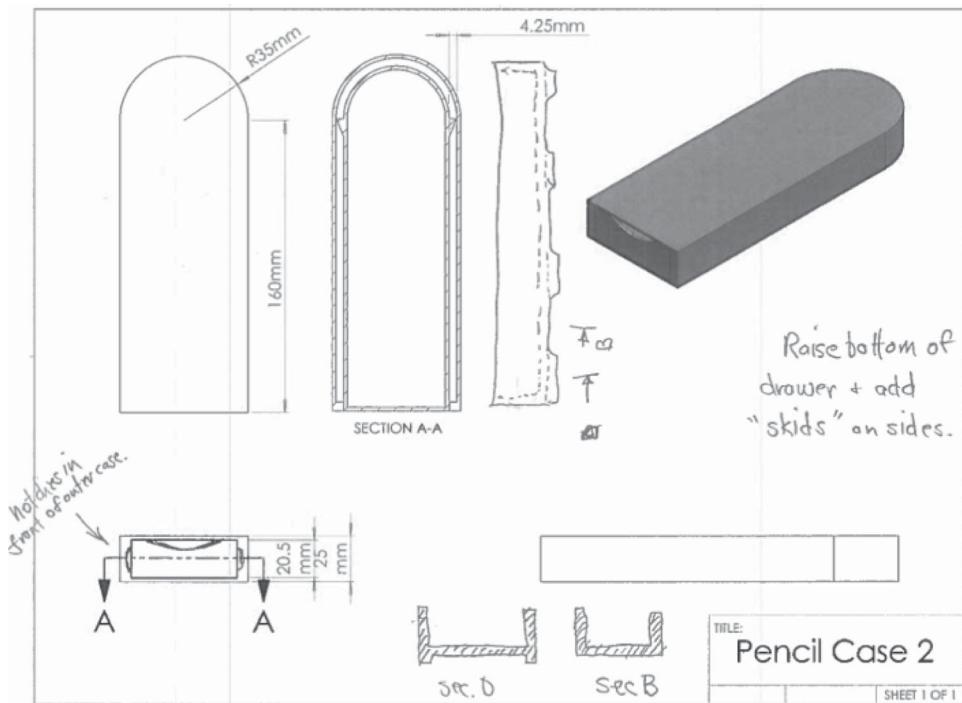


Figure A6. Sample prismatic joint problem redesign.

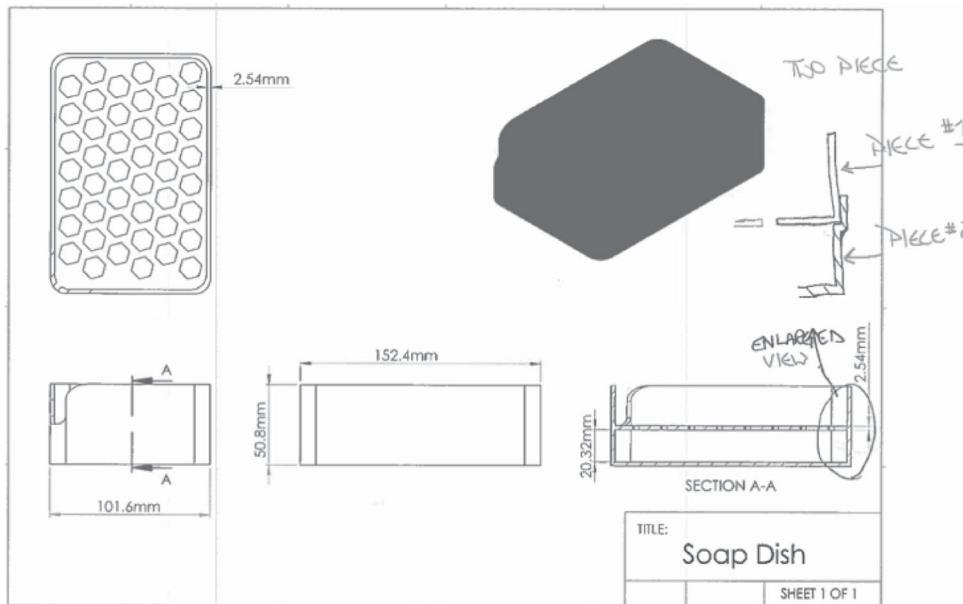


Figure A7. Sample trapped support problem redesign.

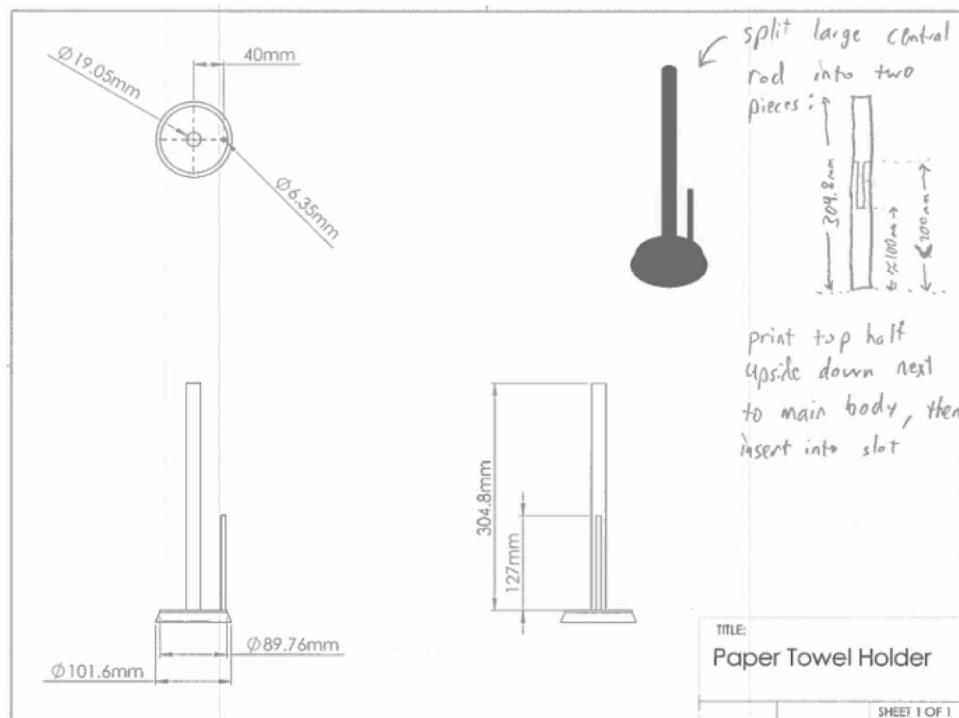


Figure A8. Sample part size problem redesign.