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The Design for Additive Manufacturing Worksheet

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ABSTRACT

Additive manufacturing (AM) technologies have become integral to modern prototyping and manufacturing. Therefore, guidelines for using AM are necessary to help users new to the technology. Many others have proposed useful guidelines, but these are rarely written in a way that is accessible to novice users. Most guidelines 1) assume the user has extensive prior knowledge of the process, 2) apply to only a few AM technologies or a very specific application, or 3) describe benefits of the technology that novices already know. In this paper, we present a 1-page, visual design-for-additive-manufacturing worksheet for novice and intermittent users which addresses common mistakes as identified by various expert machinists and additive manufacturing facilities who have worked extensively with novices. The worksheet helps designers assess the potential quality of a part made using most AM processes and indirectly suggests ways to redesign it. The immediate benefit of the worksheet is to filter out bad designs before they are printed, thus saving time on manufacturing and redesign. We implemented this as a go-no-go test for a high-volume AM facility where users are predominantly novices, and we observed an 81% decrease in the rate of poorly designed parts. We also tested the worksheet in a classroom , but found no difference between the control and the experimental groups. This result highlights the importance of motivation since the cost of using AM in this context was dramatically lower than real-world costs. This second result highlights the limitations of the worksheet.

1 INTRODUCTION

Many researchers and industry practitioners have proposed various guidelines for additive manufacturing (AM). However, the guidelines produced to date have limited usefulness for novice and intermittent users of AM processes such as 3D printing. Most guidelines discuss matters already commonly understood by novices (e.g., that AM allows complex geometries) or beyond the scope of most novices or infrequent users (e.g. how to produce specific micro and macro features in a

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part). The remaining guidelines tend to be specific for one or two technologies, but not generalizable.

This need is especially urgent since access to AM is increasing quickly [1]. For example, many universities and K-12 classrooms have introduced classes exposing students to 3D printing [2–7], or built 3D printing centers. In one case, one university introduced a "vending machine" style 3D printer bank, and reported finding that students greatly increased casual exploration of the technology [8]. We also observed in our own work with industry that many engineers at smaller companies are investigating AM as a possible addition to their company, but are wary of the possible difficulties with the technology.

We therefore saw a need in industry and academia for generalized AM guidelines that simultaneously guide and educate novice and infrequent users in the best-practices for AM. We have developed the worksheet presented in this paper to address this need. Our definition of AM is used for both rapid prototyping (RP) and rapid manufacture (RM). This paper gives a background on Design for Additive Manufacturing (DfAM) principles, the worksheet, and the validation of the worksheet. We recommend this worksheet for companies and/or individual engineers that are considering or learning new AM processes, such as 3D printing. We also recommend the worksheet for design and manufacturing courses, hobbyists, Maker clubs, and maker-spaces.

2 BACKGROUND

The DfAM literature tends to highlight the need to shift how designers think when designing parts. This need is driven by the contrast between traditional subtractive manufacturing processes and AM. AM affords new modes of manufacture that are capable of geometries not possible using subtractive methods and batch sizes that allow customized parts to become economical [9, 10], possibly enabling long-term visions such as mass-customization [10, 11].

However, AM has different limitations from those of subtractive methods. Therefore, Design for Manufacture (DfM) does not apply in the scope of the AM processes [9, 12]. These differences are increasingly important as AM continues to expand beyond rapid prototyping (RP) into end-use rapid manufacturing (RM). For example, where traditional manufacturing limitations would require a complex assembly, AM could allow for a single, pre-assembled build [13, 14]. Another interesting example is using scanning and 3D printing for the manufacture of replicas of archaeological artifacts, where non-contact preservation methods are preferable [15]. Thus, there is a need for DfAM methods similar to DfM that consider the unique affordances and limitations of AM for both RP and RM. Thompson et al. give a comprehensive, detailed review of current trends, case studies, possibilities, and limitations for additive manufacturing [9]. In addition to the need for DfAM tools that we discuss here, they also touch on many, many more topics of interest to the community.

The existing literature referred to as "DfAM" can be categorized into three groups (see table 1). The first of these groups proposes specific design methods that utilize additive manufacturing or describe how DfAM should be part of the entire design process. For example, Klahn et al. [16] describe two strategies for using AM in design: a "manufacturing-driven design strategy" which uses AM for rapid prototyping and a "function-driven design strategy" which uses the unique advantages of AM for final production parts. Another example is Campbell et al. who have studied using parametric CAD approaches to engaging customers and using AM to manufacture their customized parts [11]). However, not all of these research groups provide specifics about their proposed methods; rather many just advocate for more research.

The second group researches different approaches for pushing the boundaries of AM. This includes works on achieving

Table 1. Different versions of “design for additive manufacturing” grouped by focus

Design Methods	AM Technologies	DfAM Guidelines
Campbell et al. [11]	Adam & Zimmer [20]	Adam & Zimmer [20]
Diegel et al. [21]	Dede et al. [22]	Ameta et al [23]
Doubrovski et al. [24]	Garland & Fadel [25]	Diegel et al. [21]
Evans & Campbell [26]	Gibson et al. [27]	Meisel & Williams [28]
Gibson et al. [27]	Gorguluarslan et al. [29]	Panesar et al. [30]
Hague et al. [31]	Kruth et al. [32]	Pruss & Vietor [33]
Hague et al. [12]	Maute et al. [34]	Rosen [35]
Klahn et al. [16]	Meisel & Williams [28]	Rosen [36]
Laverne et al. [13]	Morton et al. [37]	Yang & Zhao [38]
Madden & Deshpande [39]	Panesar et al. [30]	Chernow et al. [40]
Morton et al. [37]	Ponche et al. [41]	
Ponche et al. [41]	Pruss & Vietor [33]	
Rosen [19, 35, 36]	Snyder et al. [42]	
Samperi et al. [43]	Stankovic et al. [44]	
Schmelzle et al. [14]	Ulu et al [45]	
Stankovic et al. [44]	Vayre et al. [46]	
Vayre et al. [46]	Williams et al. [47]	
Yang & Zhao [38]	Yim & Rosen [48]	
	Witherell et al. [17]	
	Truby & Lewis [18]	
	Truby & Lewis [49]	

very small features, for example, or reducing the need for support structures. It also includes works on specific applications that require a tailored process such as printing metals, biological tissues, or other exotic materials. For example, metals AM requires specialized conditions and extreme temperatures to create viable end-use parts [17] whereas bioprinting requires both delicate placement and radically different modes of thinking for bio-inspired materials [18, 19].

The third group is the most closely related to the purpose of our work. It focuses on general DfAM guidelines that highlight challenges unique to AM relative to traditional manufacturing processes. These guidelines are usually intended to be used at any point during the design, but especially between the creation of a CAD model and a manufactured prototype.

2.1 Generalized DfAM Considerations

The literature that defines any DfAM guidelines shows common themes (see table 2). Some of these commonalities include the effect of part orientation [21, 27, 31], the inclusion of manufacturing features [27], and the blunting of extreme points [20]. The importance of these guidelines is that they can be used for different types of AM processes and need to be considered in most designs. Some guidelines are important for the design process, while others describe how to use the technology, such as the reorientation of a part in the respective AM machine software. Additionally, some designs can be effective, despite ignoring some guidelines. Most designs that ignore general guidelines require specialized manipulation of the AM machines or software by experts. Despite these caveats, the development of DfAM rules or guidelines will continue to show commonalities among them until the next novel manufacturing or prototyping process is invented and requires a new

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Table 2. Guidelines described by prior papers

Principle	Description
Part orientation	Some shapes print better in certain orientations, though sometimes there is no optimal direction [9,23,27,30].
	Orientation can have an effect on the surface finish of the part, especially when dealing with rounded features [9, 21, 28, 31, 33].
	The orientation can have an effect on the strength between the horizontal and vertical components (since layers are added in the vertical 'z' direction) [9, 21, 23, 33].
Removal of supports	Removing support structures significantly reduces surface finish and increases the need for post-processing [9, 27].
	Sharp inner edges can reduce the need for support structures as the layers build [20, 31, 33].
Hollowing out parts	When functionally possible, thick walls and hollow interiors can reduce print time [9, 27, 38].
Manufacturing features	While AM does not require undercuts, draft angles, and other process specific considerations, many parts are prototypes that will eventually be manufactured using traditional processes [9, 16, 27].
Interlocking features	AM processes have a finite build space, and may require large parts to be broken up and joined later with interlocking features [27].
	It is important to ensure that joined/interlocking gap dimensions are minimized to enable robust removal of support structures and ensure small dimensional deviations [20].
Reduction of part count	If the AM part is intended as a final product, the number of parts in an assembly may be reduced [9, 23, 27, 38].
Identification marks	When a company produces many parts, it is easy to lose track of which model is which [27].
Avoid sharp edges	Removing these results in better accuracy; rounding radii correlate with outer radii of simple-curved elements [20].
Round inner edges	Rounding the edges simplifies the removal of disperse support structures (e.g. powder) [20].
Blunt extreme points	Vertical points should be blunted parallel to build plane; horizontal points should be blunted orthogonal to build plane [20].
Short overhang	This ensures robust manufacturability and prevents falling off of layers [20].
Low Island Positions	This will have a significant impact on the build times [20].

set of guidelines.

While the guidelines shown in table 2 are useful and effectively convey expert knowledge, past efforts are often worded in a way that is easy for intermediate users to understand, but not novices. For example, few novices will know what a support or an island is without further reading or experience. Some guidelines are more specific than most novice or intermediate users need or understand, or would only be necessary if an AM user creates many parts, such as putting identification markings on parts. Several guidelines, especially those by Adam and Zimmer [20], tend to be out of the control of many novices who use hobby printers, such as controlling the size of an island. Additionally, few of these appear to address common mistakes made by novices.

3 THE DfAM WORKSHEET

The DfAM worksheet can be found in figure 1. This sheet is designed for novices to additive manufacturing. It is also useful for intermittent or intermediate users as a checklist to go through for validating a design prior to manufacture.

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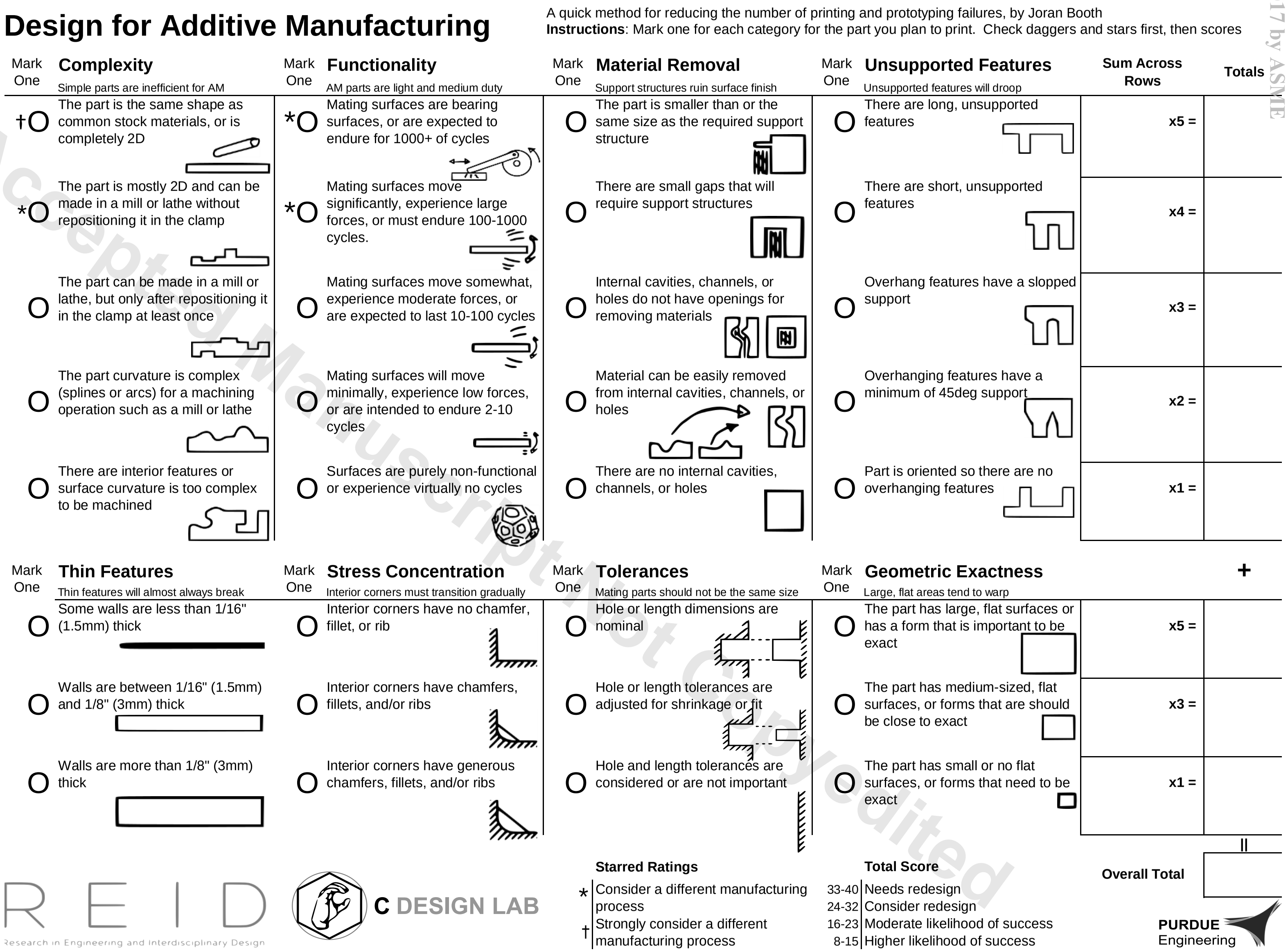

Design for Additive Manufacturing

A quick method for reducing the number of printing and prototyping failures, by Joran Booth
Instructions: Mark one for each category for the part you plan to print. Check daggers and stars first, then scores

Mark One	**Complexity** Simple parts are inefficient for AM	Mark One	**Functionality** AM parts are light and medium duty	Mark One	**Material Removal** Support structures ruin surface finish	Mark One	**Unsupported Features** Unsupported features will droop	Sum Across Rows	Totals
†○	The part is the same shape as common stock materials, or is completely 2D	*○	Mating surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles	○	The part is smaller than or the same size as the required support structure	○	There are long, unsupported features	x5 =	
*○	The part is mostly 2D and can be made in a mill or lathe without repositioning it in the clamp	*○	Mating surfaces move significantly, experience large forces, or must endure 100-1000 cycles.	○	There are small gaps that will require support structures	○	There are short, unsupported features	x4 =	
○	The part can be made in a mill or lathe, but only after repositioning it in the clamp at least once	○	Mating surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles	○	Internal cavities, channels, or holes do not have openings for removing materials	○	Overhang features have a slopped support	x3 =	
○	The part curvature is complex (splines or arcs) for a machining operation such as a mill or lathe	○	Mating surfaces will move minimally, experience low forces, or are intended to endure 2-10 cycles	○	Material can be easily removed from internal cavities, channels, or holes	○	Overhanging features have a minimum of 45deg support	x2 =	
○	There are interior features or surface curvature is too complex to be machined	○	Surfaces are purely non-functional or experience virtually no cycles	○	There are no internal cavities, channels, or holes	○	Part is oriented so there are no overhanging features	x1 =	

Mark One	**Thin Features** Thin features will almost always break	Mark One	**Stress Concentration** Interior corners must transition gradually	Mark One	**Tolerances** Mating parts should not be the same size	Mark One	**Geometric Exactness** Large, flat areas tend to warp		+
○	Some walls are less than 1/16" (1.5mm) thick	○	Interior corners have no chamfer, fillet, or rib	○	Hole or length dimensions are nominal	○	The part has large, flat surfaces or has a form that is important to be exact	x5 =	
○	Walls are between 1/16" (1.5mm) and 1/8" (3mm) thick	○	Interior corners have chamfers, fillets, and/or ribs	○	Hole or length tolerances are adjusted for shrinkage or fit	○	The part has medium-sized, flat surfaces, or forms that are should be close to exact	x3 =	
○	Walls are more than 1/8" (3mm) thick	○	Interior corners have generous chamfers, fillets, and/or ribs	○	Hole and length tolerances are considered or are not important	○	The part has small or no flat surfaces, or forms that need to be exact	x1 =	

=

Overall Total

Starred Ratings

*	Consider a different manufacturing process
†	Strongly consider a different manufacturing process

Total Score

33-40	Needs redesign
24-32	Consider redesign
16-23	Moderate likelihood of success
8-15	Higher likelihood of success

Fig. 1. The DfAM worksheet is designed for novices and intermittent users of additive manufacturing technologies.

3.1 Process for Creating the Sheet

To create the sheet, we started by reflecting on our own experiences with 3D printing and laser cutting, running 3D printing labs, and teaching design courses where students use 3D printing. We then consulted with lab monitors at the

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Boilermaker Lab at Purdue to identify several common mistakes that students make. We grouped and abstracted these principles into considerations and developed scales for these. Next, we consulted with two experts, a machinist with two decades of experience with AM and a machine design researcher with extensive experience teaching senior design, who are familiar with common novice mistakes. We used these consultations to iterate and refine the worksheet.

After the worksheet was near final form, we consulted with three high-volume 3D printing labs to see if the worksheet addressed their common concerns. The three labs were the Purdue Boilermaker Lab, the Purdue Mechanical Engineering 3D Printing Lab, and the Faboratory. The Boilermaker lab serves all of the Purdue campus and features several types of extrusion-type 3D printers. The Mech Eng. 3D Printing Lab serves several design courses and department needs in general. The lab manager, who was also the first expert, had over 20 years of experience in AM and operated two SLA machines and three FDM printers. The Faboratory is a soft-robotics research laboratory and uses several cutting-edge AM processes on micro and macro scales. All three labs confirmed that the worksheet addressed relevant concerns and that it was not missing any major criteria. One member of the Faboratory suggested that the worksheet should include some scales for intended use and material properties. We omitted these categories since most novices only have one or two AM processes available to them. These considerations are more relevant for expert practitioners who must frequently choose among several AM processes.

3.2 Considerations for the Worksheet

The goals of the worksheet are to 1) reduce print failures, 2) improve understanding of AM limitations for novice users, and 3) recommend a course of action. Some essential features of the worksheet are that it is short, very easy to use, very fast to use, and gives appropriate recommendations. We argue that an additional consideration must be that industry will often not adopt a new method unless it is very easy to use or required by management. This worksheet is designed to be reminiscent of DfM worksheets to aid in industry adoption. The worksheet is also confined to a single page to reduce complexity.

The considerations we address in the worksheet are not comprehensive, but are the most prominent issues based on our qualitative observation and expert consultations. While we took multiple processes into account, our primary consultations were with experts most familiar with extrusion and SLA processes. The four categories in the top half of the worksheet address the most common problems we observed. These are part complexity, intended function, plans for material removal, and unsupported features. The bottom four categories address common mechanical design problems that affect the strength or integrity of the part. These are excessively thin features, part strength, part tolerances, and the effect of warping on geometric tolerances.

The most common problem we saw is that many novices used AM for parts that are easier to make with other methods. For example, we saw many novices making axles, plates, and gears using AM instead of cutting metal rods on a bandsaw or simply buying the parts. We also observed that many users expected the AM parts to endure a similar number of cycles as a machined part. Also, material removal and support structures were commonly ignored by novices. For example, many novices using an SLA process created hollow parts but did not include holes to drain fluid from the cavities. Additionally, many novices did not consider the poor surface quality left by the support structures or the drooping seen in unsupported

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features.

Our worksheet does not address all of the possible AM considerations. But it does return a qualitative assessment of risk of failure, rather than directly evaluating the quality of the design. And since the assessment is qualitative, it lumps manufacturing, assembly, and mechanical failures into a single score.

3.3 How to Use the Worksheet

The worksheet may be used at the conceptual stage (preferred) or at the CAD stage, but should be used prior to manufacturing a part. The eight categories are listed in columns, and a scale is found below each category title. A user marks how the design fares on the scales in each category. When all the marks are complete, the user sums the total for each row and multiplies the sum to get a total for each row. The totals are then summed to calculate an overall score.

The user then examines the two scoring schemes at the bottom of the worksheet. The first scoring scheme is a go-no-go assessment based on the first two categories only. If the no-go condition is flagged, the user is instructed to search for a simpler manufacturing method. If the design survives the first scoring scheme, the second scoring scheme suggests a likelihood of the part being of good quality. If the score is high, the user should consider redesign. If it is low, they can expect a higher likelihood of success. After the first time using the sheet, the user can glance at the images on the sheet to remind them of the scale levels rather than reading each question.

When using the worksheet, it should be used primarily to provoke reflection on the design [50], which is augmented further by mentoring with a TA or other instructor. In this regard, the worksheet is similar to design methods such as QFD where the value of the method is to get teams to talk to each other [51, 52]. However, like QFD, designers will encounter problems if they rely too much on the numerical output of the method since it is rather easy to sway the outcome. For example, when we tested the worksheet with different independent raters on 13 parts, the agreement level was 0.4, using the intraclass correlation coefficient. We caution users of the worksheet against using it as a quantitative measure of how good a design is, as it is not intended to be used in that way. This is the reason the worksheet uses ranges of scores to determine the end recommendation. It is also why the worksheet makes never makes a definite statement that the user will be successful.

4 EVALUATION OF THE WORKSHEET

To evaluate the effectiveness of the worksheet, we wanted to know if the design cycle was positively affected by the worksheet through reducing the number of iterations a designer must take to create a viable part. We used two different approaches to validate the worksheet. For the first approach, we tracked print logs in a high-volume 3D printing laboratory to see how using the worksheet affected the number of failed prints and reprints. For the second validation, we measured what students in a toy design course that requires 3D printing as a part of the course project learned from the worksheet.

4.1 Validation 1: Print Failures

We chose to measure print logs rather than conduct an experimental or ethnographic study because these other approaches would necessarily restrict sample size. In studying the print logs, we assumed that 1) if a part fails, it is reprinted later, and 2) all failed prints are reprinted through the same service.

Table 3. Changes in the print failure and reprint rate due to introducing the DfAM worksheet, including a reduced set of data

	w/o DfAM	w/ DfAM	Change	p (χ^2)	Odds Ratio
n	181	33			
Prints failed due to bad design	18.2%	0%	100% decrease	0.028	∞ (large)
Design reprinted	14.9%	6.0%	59.4% decrease	0.381	2.46 (medium)
Combined failure rate	33.1%	6.0%	81.7% decrease	0.007	5.52 (large)

We collaborated with the Boilermaker Lab, a high-volume 3D printing facility which serves the entire Purdue University campus, on measuring the effect of the worksheet. We kept logs of print jobs over a period of about a month without using the worksheet. We then kept logs of print jobs for another month after introducing the worksheet to the lab and requiring all print submissions to have first completed the sheet. If students received a "redesign" recommendation from the sheet, they were asked to improve the part and resubmit it later.

All printers used for the study were Makerbot Replicators, each with 2000+ service hours. The data we collected included timestamps, filenames, whether the print failed, why the print failed, whether the DfAM worksheet was used, and the score from the worksheet. We used filenames to track if redesigned parts were resubmitted after an initial print.

When compiling the data, we removed print failures from the data set if they were clearly due to a problem with the machine. If there was any question as to the cause of the failure, we assumed it was due to the design being bad. Common reasons to exclude failed prints were improper build plate leveling or nozzles jamming.

The scores from the DfAM worksheet were recorded in a digital version of the worksheet hosted on Qualtrics. Volunteers kept the print logs and enforced use of the worksheet, so not all prints from the second month used the worksheet. Similarly, the print log was not always complete and therefore the Qualtrics data could not be mapped directly to the print logs.

We used this data to answer three questions.

- How long does using the worksheet take?
- Does the DfAM worksheet reduce the number of design iterations as measured by the quantity of printer errors and part revisions (i.e., reprints)?
- What are the most commonly reported design problems with novice designs?

According to the survey log from Qualtrics, the number of samples was 102, the median time spent on the worksheet was 2.7 minutes, and the average was 5.4 minutes with a standard deviation of 8.7 minutes. Three observations were removed due to being longer than four hours because it is almost certain that in these cases the browser was left open. This time frame confirms that the worksheet is fast to use.

To analyze the second question, we split the print log data collected at the Boilermaker Lab into two groups: prints which did not use the worksheet and prints which did. We then counted the number of failures in each group and divided these by the total number of prints in each group to get a failure rate. We also used the file name to determine how many prints were repeated. The reprint rate was how many parts were reprinted divided by the total. Summary statistics can be found in table 3.

Table 4. The average and standard deviation of scores reported from the DfAM worksheet. Lower averages are preferable. The most commonly reported problems with the designs were functionality and tolerances.

	Complexity	Functionality	Unsupported Features	Material Removal	Thin Features	Stress Concen.	Tolerances	Geometric Features
Avg.	3.76	4.53	2.82	3.83	3.39	1.85	4.39	2.85
St. D.	1.06	0.81	1.53	1.13	1.00	1.48	1.04	1.70

The overall changes we observed were quite dramatic. The number of failures dropped 83% after the implementation of the DfAM worksheet. We also observed that there were no third reprints done after the worksheet was implemented, though this may change with more samples. So we can conclude that the worksheet had a positive effect on the design cycle time since the number of failures decreased significantly.

We performed three checks to see how sensitive these analyses were to small changes. First, we added one imaginary failure to the bad design category, and found that the result was still statistically significant and the effect size was 6.02 for failed prints, and 3.64 for combined failures (both large). This result is comparable to the combined failure rate and shows that the effect size is robust to additional data. Second, we repeated the analysis with a subset of data to see if the month when the data was collected had an effect. Since some data with and without the worksheet was collected concurrently, we analyzed the data from this month only. The results line up with our original analysis. The combined failure rate decreased by 92% and had an odds ratio of 12.99 (large). In the third check, we analyzed what would happen if our two assumptions were violated and prints were repeated elsewhere. For this check, we doubled the number repeated prints for the non-DfAM group and set the rate of reprints for the DfAM group equal to the non-DfAM group. The result is still statistically significant, but the odds ratio is much smaller for the combined failure rate, at 1.6 (small). The first two sensitivity analyses show the same magnitude and direction as our original analysis. The third sensitivity analysis shows the same result, but the effect is much smaller. These confirm that our analysis is accurate, but the scale of the effect may differ depending on how accurate our assumptions are.

For the third question, we looked at the average ratings for each category on the worksheet. The most commonly reported problems with the designs were functionality (4.54 avg.) and tolerances (4.39 avg.). See table 4 for more statistics. We also qualitatively compared existing part designs to the ratings the sheet yielded for those parts. We found that the ratings of the sheet were consistent, even at the boundaries between the two rating levels. Several examples can be found in table 2.

4.2 Validation 2: In-Class Testing for Learning Outcomes

As a second validation, we tested the worksheet on students enrolled in a Computer Aided Design and Prototyping course at Purdue University, ME 444. The participants were senior level undergraduate students and all agreed to participate in the study. Most of them were studying mechanical engineering, while others were studying aerospace, astronautical, biomedical, biological, or interdisciplinary engineering.

The course consisted of two lab sections. To assess the impact of the worksheet, only one lab section was selected to use the worksheet, while the other acted as a control group.

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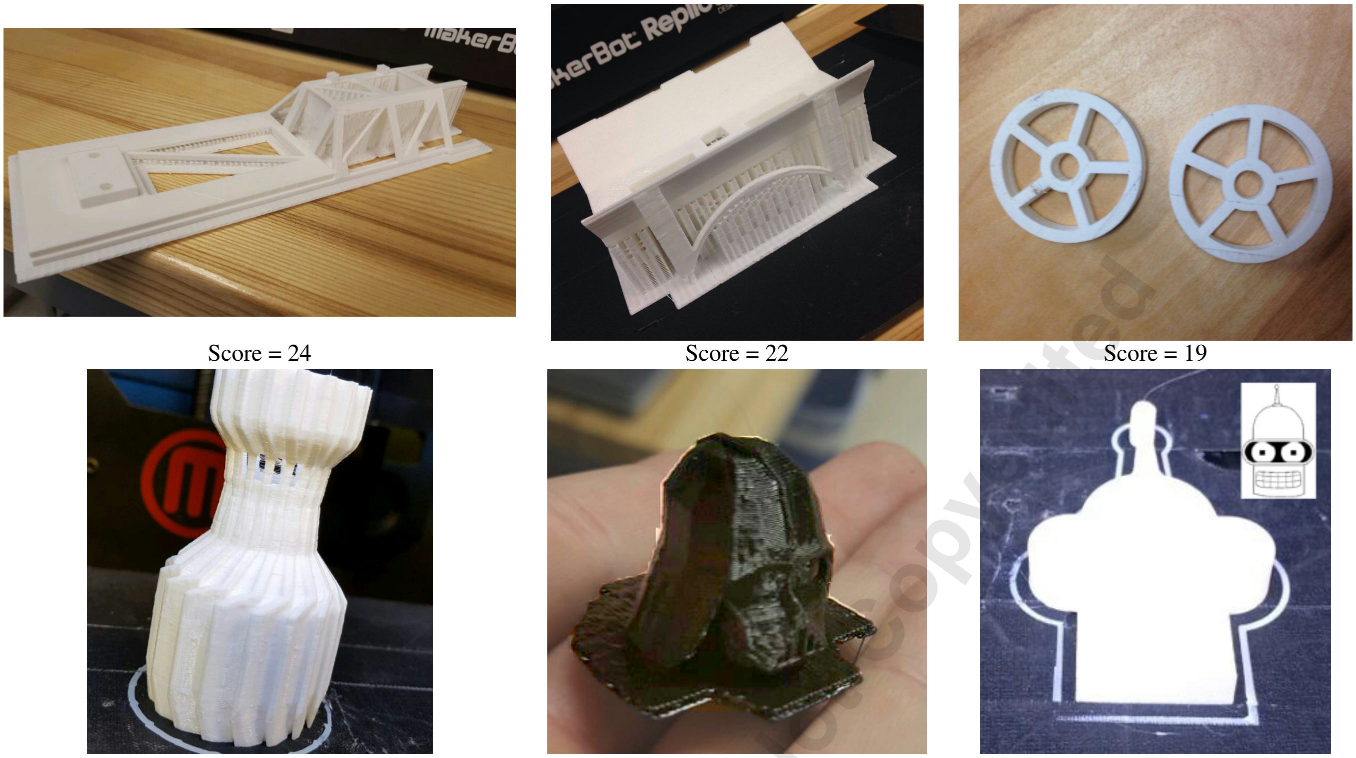
Fig. 2. Examples of prints created after students used the DfAM worksheet. A lower score rates better on the worksheet. The bottom right image is of a cartoon robot head.



Score = 24 Score = 22 Score = 19

Score = 16 Score = 15 Score = 11

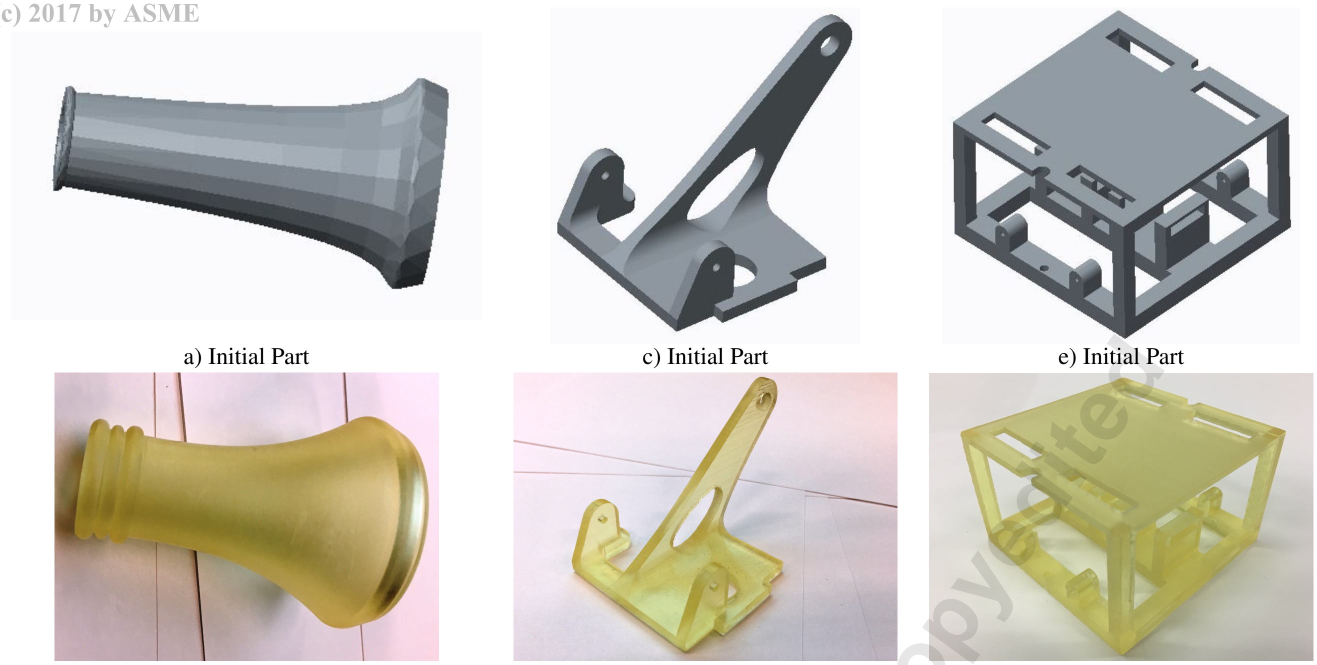
4.2.1 Course and Project Details

The focus of the ME 444 course has been described previously [3]. The course teaches advanced CAD skills and design thinking. The students showcase their learning by creating a novel toy then manufacturing it by the end of the semester. For this final project, students are required to incorporate a minimum number of AM components (limited by total print volume) into the functional mechanisms that drive their toys. While students are not charged any money to use the ultra-high resolution 3D printing, they are encouraged to employ laser cutting and other rapid prototyping techniques. When students print their design, it is oriented, printed, and post-processed by a professional machinist.

4.2.2 Measures and Procedures

The study consisted of three phases: 1) a pre-assessment, 2) an individual assignment to assess what potential problems a part might have for AM, and 3) a post-assessment which repeated the same questions as the pre-assessment. In addition to the pre/post assessment, we collected the CAD files and pictures of the final prints for each part used in the assignment.

The pre and post assessments were administered with two months between them to reduce any potential testing bias. The assessment consisted of 12 models which were each accompanied by a short questionnaire. In each questionnaire, students were first asked to evaluate, using a Likert scale, a prescribed 3D CAD model for how likely it would be successfully printed on a 3D printer. Students were asked to identify possible features that would increase print difficulty (if they existed) by clicking on all areas of the image they believed did so. Students were then asked what they would do to improve the model,


a) Initial Part c) Initial Part e) Initial Part

b) Final Part d) Final Part f) Final part

Fig. 3. Examples of parts from the second study. Sub-figures a) and b) show one of only three examples of any changes made. The other two examples show no change from pre to post. All three changes we observed were unrelated to improving the manufacturability.

if at all, to make it easier to 3D print. Finally, students were asked, using a Likert scale and an open-ended reply, to consider how much they agreed with the following statement: Even if this model can be 3D printed, it would be better to use a different manufacturing process.

A week after the pre-assessment, students completed the DfAM assignment. After submitting their initial CAD designs, individuals in both groups were asked to select a single part and evaluate its fitness for 3D printing. The control group was asked to write a short paragraph explaining what needed to be changed, and why. The experimental group was given the DfAM worksheet as a guide. This assignment was graded upon completion only.

After the assignment, we took pictures of parts as they were printed and after they were post-processed. We also logged if and why any models were re-submitted for printing and the changes that were made from the initial model. At the end of the semester, after final projects were submitted, we asked students to take do post-assessment, which asked the same questions as the pre-assessment. The results from the pre/post assessment and the part models were compiled and analyzed after the semester was over.

4.2.3 Results

We observed no statistical or practical differences between the group that used the DfAM worksheet and the group that printed their own parts in any of our data sources. Among all 60 individuals, only three made any changes to their parts, and all the changes we observed were unrelated to manufacturability. Figure 4.2.3 shows three examples of parts: the one part with the most significant changes in our data-set and the two that were unchanged.

The results for the parts submitted by students for printing show that not many changes were made to the parts by either lab section. The lab section that filled out the DfAM worksheet had most students rate their parts between 24-32 on the worksheet which suggests "consider re-design" while just one part was rated 33. The results show that only one student redesigned their part by changing dimensions, adding grooves and rounding corners (see a) and b) in Figure 4.2.3). As for the control group, the majority believed that their parts would be successfully printed and only two parts were changed before printing by adding additional holes to a part in one and rounding the edges in the other.

The pre/post assessment responses were compared in a paired t-test in order to determine whether or not there was a significant change in student responses. Neither the control group nor the group using the study showed a statistically or practically significant change in their responses in the pre/post assessment. We validated this model with other models, including a general linear model which controlled for experience with 3D printing and nesting within labs.

5 DISCUSSION

In one validation study, we saw a significant change in the designs that novices produced. In the other study, we saw no difference. The differences between these two studies give us an idea of when the worksheet is useful and when it is not.

In the first validation study, we saw a significant decrease in poor designs. One key aspect of this study was that the designs were evaluated with a volunteer lab monitor prior to being printed, and designs below a certain threshold were not printed at all. This effectively forced novices to evaluate their designs and iterate when they were not good enough.

In the second validation study, we saw no differences between the in-class group that used the worksheet and the group that did not. This result was the same for both the pre/post assessments and the analysis of the designs submitted for the class. This result surprised us, until we realized that almost no students in either group made any changes to their design from the time it was initially submitted to its final submission. Among all 60 designs that we evaluated, only three were changed at all, and that was in mostly superficial ways unrelated to manufacturability. This leads us to believe that students did not iterate their design once it was created in the CAD system and therefore did not use the worksheet to improve their design.

Our interpretation of the results aligns with research on the use of CAD in the design process. The use of CAD too early in design is shown to be associated with a sunk cost effect, and an unwillingness to change a design [53–56]. This effect is also observed with physical models [57], underscoring the need to use this worksheet before ideas have set in.

The lack of iteration in the designs from the second validation study seems to also underscore the role of incentives and opportunity costs (i.e. availability) in the effectiveness of the worksheet. In the class we studied, students were only given one opportunity to print their models on the high precision printer as a final prototype. They were able to use extrusion-based printers prior to this, but it was rare for teams to do so. Additionally, the cost of printing was free to students enrolled in the course, and when the final print was made, the students submitted the part to a manufacturing professional who oriented, printed, and post-processed the parts for them. This means that the cost of printing for these students was effectively negligible, thus dramatically influencing their decision to iterate or accept a design.

We posit that this lack of cost to the students caused them not to iterate or even to improve their designs since there was little consequence for mistakes. Availability and cost are shown to be important factors in other design steps. When

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engineers describe their information gathering steps during design, they report that they strongly favor what is available over what is optimal [58]. This also aligns with our experience with the course in prior semesters. We have often observed designs that included parts that should be manufactured using other, simpler methods, but were created with a 3D printer anyway. In situations like these, the time and monetary cost of manufacturing an axle or plate is more than outsourcing it at no cost, and it seems likely that future students will prefer the easier option if offered. If our conclusion is true, we should expect that in workshops such as maker-spaces where the available pieces of equipment are limited, parts will commonly be made using ill-suited processes, and that this mismatch of process to part is driven entirely by availability and access.

Another key difference between the first and second validation studies was the amount of guided interaction. In the second study, students were given general advice on how to print a part, but were not given direct, personal feedback. The worksheet was distributed to students prior to the final deadline for their 3D printing model submission and instructions on the use of the worksheet were provided. However, there was no additional direct feedback given to the students regarding their design scores or what changes could be made to their models other than what was indicated on the worksheet. Additionally, the teaching staff in this course typically refrain from giving direct feedback regarding specific modeling techniques or design decisions because they do not want to impede creativity or the level of complexity by directing student projects too much. It is possible that the future inclusion of a casual design review in the design process would increase the students' motivation to learn and use better design techniques for additive manufacturing.

6 CONCLUSIONS AND RECOMMENDATIONS

In this paper, we present a design for additive manufacturing (DfAM) worksheet for novice and intermittent users of additive manufacturing (AM) technologies to improve part quality. The worksheet is unique compared to prior efforts because it accounts for users with low experience and is constructed in a way that simultaneously advises on the quality of the part and suggests improvements that can be made to it. When we implemented the worksheet in a high-volume 3D printing lab, we saw at least an 81% decrease in bad parts, which combines the number of failed prints and reprinted parts. These results demonstrate that the worksheet can help reduce the design cycle for novice and intermediate users.

However, we saw in the second validation that there are constraints in how the sheets can be effectively implemented. Based on the differences between the conditions in the first and second validation studies, it appears that a lack of iteration in the design process and an imbalance in the cost of additive manufacturing relative to other manufacturing methods can negate the motivation for novices to use the worksheet. Consequently, motivation to get a good print the first time is what drives the effectiveness of the DfAM worksheet, stemming from continual iteration and design improvement. This means that use of the worksheet should be purposeful and should complement the coursework as a teaching aid, not replace it.

Based on these results, we recommend using this worksheet in both academic and industry environments. We remind the reader that the worksheet should be used as a tool for driving designer reflection, and caution users against using it as a quantitative measure of how good a design is. While we took care to make the worksheet applicable to a wide range of AM processes, follow-up work includes creating a set of process-specific worksheets that more accurately account for limitations unique to each process. Other limitations to this work include the sampling from a single university and the potential for inconsistent print logs due to the volunteer status of those who collected them. While this may limit the potential accuracy of our results, we performed sensitivity analyses which confirmed the significance of the results. Our data from the first validation would also not capture failed parts that were abandoned due to design changes. It is difficult to know how much this would impact our analysis.

Additional limitations are that we did not exhaustively test every possible learning environment, and there may be factors we have not accounted for. Future work should consider how tools such as this can be used across disciplines, such as architecture, arts, engineering, and industrial design. Based on our results, future work should also focus on computer-based recommender systems embedded in CAD. Many of the principles in this worksheet can be measured in a CAD environment once an orientation is selected, including wall thickness, the degree to which features are unsupported, and the degree of complexity. Additionally, by embedding this work in a CAD environment, designers are more likely to see problems with their design earlier in the process.

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References

[1] Bull, G., and Groves, J., 2009. “The democratization of production.”. *Learning & Leading with Technology,* **37**(3), pp. 36–37.

[2] Bøhn, J. H., 1997. “Integrating rapid prototyping into the engineering curriculum-a case study”. *Rapid Prototyping Journal,* **3**(1), pp. 32–37.

[3] Taborda, E., Chandrasegaran, S. K., and Ramani, K., 2012. “Me 444: Redesigning a toy design course”. In Proceedings of TMCE.

[4] Fidan, I., 2012. “Remotely accessible rapid prototyping laboratory: design and implementation framework”. *Rapid Prototyping Journal,* **18**(5), pp. 344–352.

[5] Geraedts, J., Doubrovski, E., Verlinden, J., and Stellingwerff, M., 2012. “Three views on additive manufacturing: business, research and education”. In Ninth Int. Symp. Tools Methods Compet. Eng., I. Horváth, A. Albers, M. Behrendt, and Z. Rusák, Eds, pp. 1–15.

Journal of Mechanical Design. Received January 31, 2017;
Accepted manuscript posted July 13, 2017. doi:10.1115/1.4037251

[6] Chiu, J. L., Bull, G., Berry III, R. Q., and Kjellstrom, W. R., 2013. "Teaching engineering design with digital fabrication: imagining, creating, and refining ideas". In *Emerging Technologies for the Classroom*. Springer, pp. 47–62.

[7] Williams, C. B., and Seepersad, C. C., 2012. "Design for additive manufacturing curriculum: A problem-and project-based approach". In International solid freeform fabrication symposium, Austin, TX, pp. 81–92.

[8] Meisel, N. A., and Williams, C. B., 2013. "Design and assessment of an am vending machine for student use". In Proceedings of the 24th annual international solid freeform fabrication symposium, Austin (TX).

[9] Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., et al., 2016. "Design for additive manufacturing: Trends, opportunities, considerations, and constraints". *CIRP Annals-Manufacturing Technology,* **65**(2), pp. 737–760.

[10] Abdul Kudus, S. I., Campbell, R. I., and Bibb, R., 2016. "Customer perceived value for self-designed personalised products made using additive manufacturing".

[11] Campbell, R. I., De Beer, D., Mauchline, D., Becker, L., Van der Grijp, R., Ariadi, Y., and Evans, M. A., 2014. "Additive manufacturing as an enabler for enhanced consumer involvement". *South African Journal of Industrial Engineering,* **25**(2), pp. 67–74.

[12] Hague, R., Mansour, S., and Saleh, N., 2004. "Material and design considerations for rapid manufacturing". *International Journal of Production Research,* **42**(22), Nov, pp. 4691–4708.

[13] Laverne, F., Segonds, F., Anwer, N., and Le Coq, M., 2015. "Assembly based methods to support product innovation in design for additive manufacturing: An exploratory case study". *J Mech Design,* **137**(12), Oct., p. 121701.

[14] Schmelzle, J., Kline, E. V., Dickman, C. J., Reutzel, E. W., Jones, G., and Simpson, T. W., 2015. "(re) designing for part consolidation: Understanding the challenges of metal additive manufacturing". *J Mech Design,* **137**(11), p. 111404.

[15] Zhang, F., Campbell, R. I., and Graham, I. J., 2016. "Application of additive manufacturing to the digital restoration of archaeological artefacts". *International Journal of Rapid Manufacturing,* **6**(1), pp. 75–94.

[16] Klahn, C., Leutenecker, B., and Meboldt, M., 2015. "Design strategies for the process of additive manufacturing". *Procedia CIRP,* **36**, pp. 230–235.

[17] Witherell, P., Feng, S., Rosen, Simpson, T. W., Saint John, D. B., Michaleris, P., Liu, Z.-K., Chen, L.-Q., and Martukanitz, R., 2014. "Toward metamodels for composable and reusable additive manufacturing process models". *J. of Mfg. Sci. & Eng.,* **136**(6), pp. 061025–061025–9.

[18] Truby, R. L., and Lewis, J. A., 2016. "Printing soft matter in three dimensions". *Nature,* **540**(7633), pp. 371–378.

[19] Rosen, D. W., 2007. "Design for additive manufacturing: A method to explore unexplored regions of the design space". In Proceedings of the 18th Annual Solid Freeform Fabrication Symposium.

[20] Adam, G. A., and Zimmer, D., 2014. "Design for additive manufacturing: Element transitions and aggregated structures". *CIRP Journal of Manufacturing Science and Technology,* **7**(1), Jan., pp. 20–28.

[21] Diegel, O., Singamneni, S., and Withell, S. R. . A., 2010. "Tools for sustainable and product design and additive manufacturing". *Journal of Sustainable Development,* **3**, pp. 68–75.

[22] Dede, E. M., Joshi, S. N., and Zhou, F., 2015. "Topology optimization, additive layer manufacturing, and experimental

testing of an air-cooled heat sink". *J Mech Design,* **137**(11), p. 111403.

[23] Ameta, G., Lipman, R., Moylan, S., and Witherell, P., 2015. "Investigating the role of geometric dimensioning and tolerancing in additive manufacturing". *J Mech Design,* **137**(11), p. 111401.

[24] Doubrovski, Z., Verlinden, J. C., and Geraedts, J. M. P., 2011. "Optimal design for additive manufacturing: Opportunties and challenges". In Proceedings of the ASME IDETC/CIE.

[25] Garland, A., and Fadel, G. M., 2015. "Design and manufacturing functionally gradient material objects with an off the shelf three-dimensional printer". *J Mech Design,* **137**(11).

[26] Evans, M. A., and Ian Campbell, R., 2003. "A comparative evaluation of industrial design models produced using rapid prototyping and workshop-based fabrication techniques". *Rapid Prototyping Journal,* **9**(5), pp. 344–351.

[27] Gibson, I., Rosen, D. W., and Stucker, B., 2010. *Additive Manufacturing Technologies: Rapid Prototying to Direct Digital Manufacturing*. Springer, New York.

[28] Meisel, N., and Williams, C., 2015. "An investigation of key design for additive manufacturing constraints in multimaterial three-dimensional printing". *J Mech Design,* **137**(11), p. 111406.

[29] Gorguluarslan, R. M., Park, S.-I., Rosen, D. W., and Choi, S.-K., 2015. "A multilevel upscaling method for material characterization of additively manufactured part under uncertainties". *J Mech Design,* **137**(11), p. 111408.

[30] Panesar, A., Brackett, D., Ashcroft, I., Wildman, R., and Hague, R., 2015. "Design framework for multifunctional additive manufacturing: Placement and routing of three-dimensional printed circuit volumes". *J Mech Design,* **137**(11), p. 111414.

[31] Hague, R., Campbell, I., and Dickens, P., 2003. "Implications on design of rapid manufacturing". *J Mech Eng Sci,* **217 Part C.**, pp. 25–30.

[32] Kruth, J. P., Leu, M. C., and Nakagawa, T., 1998. "Progress in additive and manufacturing and rapid and prototyping". In Annals of the CIRP, no. on.

[33] Prüß, H., and Vietor, T., 2015. "Design for fiber-reinforced additive manufacturing". *J Mech Design,* **137**(11), p. 111409.

[34] Maute, K., Tkachuk, A., Wu, J., Qi, H. J., Ding, Z., and Dunn, M. L., 2015. "Level set topology optimization of printed active composites". *J Mech Design,* **137**(11), p. 111402.

[35] Rosen, D., 2015. "Design for additive manufacturing: Past, present, and future directions". *J Mech Design,* **136**(9), p. 090301.

[36] Rosen, D. W., 2014. "What are principles for design for additive manufacturing?". *Proceedings of the 1st International Conference on Progress in Additive Manufacturing*.

[37] Morton, P. A., Mireles, J., Mendoza, H., Cordero, P. M., Benedict, M., and Wicker, R. B., 2015. "Enhancement of low-cycle fatigue performance from tailored microstructures enabled by electron beam melting additive manufacturing technology". *J Mech Design,* **137**(11), p. 111412.

[38] Yang, S., and Zhao, Y. F., 2015. "Additive manufacturing-enabled design theory and methodology: a critical review". *Int J Adv Manuf Technol,* **80**(1-4), Mar, pp. 327–342.

[39] Madden, K. E., and Deshpande, A. D., 2015. "On integration of additive manufacturing during the design and development of a rehabilitation robot: A case study". *J Mech Design,* **137**(11), p. 111417.

[40] Chernow, E., Samperi, M., Joshi, S., and Simpson, T., 2013. "A process planning framework for lens metal additive manufacturing". In IIE Annual Conference. Proceedings, Institute of Industrial Engineers-Publisher, p. 2377.

[41] Ponche, R., Hascoet, Y., Kerbrat, D., and Mognol, P., 2012. "A new global approach to design for additive manufacturing". *Virtual and Physical Prototyping,* **7**(2), pp. 93–105.

[42] Snyder, J. C., Stimpson, C. K., Thole, K. A., and Mongillo, D. J., 2015. "Build direction effects on microchannel tolerance and surface roughness". *J Mech Design,* **137**(11), p. 111411.

[43] Samperi, M., Chernow, E., Simpson, T., Joshi, S., and Talbot, M., 2013. "Towards a process workflow for designing and fabricating parts using additive manufacturing". In 2013 RAPID Conference and Exposition, Pittsburgh, PA, June, pp. 10–13.

[44] Stanković, T., Mueller, J., Egan, P., and Shea, K., 2015. "A generalized optimality criteria method for optimization of additively manufactured multimaterial lattice structures". *J Mech Design,* **137**(11), p. 111405.

[45] Ulu, E., Korkmaz, E., Yay, K., Ozdoganlar, O. B., and Kara, L. B., 2015. "Enhancing the structural performance of additively manufactured objects through build orientation optimization". *J Mech Design,* **137**(11), p. 111410.

[46] Vayre, B., Vignat, F., and Villeneuve, F., 2012. "Designing for additive manufacturing". In Procedia CIRP, Vol. 3, Elsevier BV, p. 632637.

[47] Williams, C. B., Mistree, F., and Rosen, D. W., 2011. "A functional classification framework for the conceptual design of additive manufacturing technologies". *J Mech Design,* **133**(12), p. 121002.

[48] Yim, S., and Rosen, D. W., 2011. "A framework for self-realizing process models for additive manufacturing". In Proceedings of ASME IDETC/CIE.

[49] Gladman, A. S., Matsumoto, E. A., Nuzzo, R. G., Mahadevan, L., and Lewis, J. A., 2016. "Biomimetic 4d printing". *Nature Materials*.

[50] Schon, D. A., 1984. *The reflective practitioner: How professionals think in action*, Vol. 5126. Basic books.

[51] Hauser, J. R., and Clausing, D., 1996. "The house of quality". *IEEE Engineering Management Review,* **24**(1), pp. 24–32.

[52] Juarez, J., Gunther, E., and Toomey, J., 1990. "Quality function deployment applied to an als cryogenic tank". In Aerospace Engineering Conference and Show, p. 1807.

[53] Lawson, B., 2002. "Cad and creativity: Does the computer really help?". *Leonardo,* **35**.

[54] Robertson, B., and Radcliffe, D., 2009. "Impact of cad tools on creative problem solving in engineering design". *CAD,* **41**(3), pp. 136 – 146. Computer Support for Conceptual Design.

[55] Walther, J., Robertson, B., and Radcliffe, D., 2007. "Avoiding the potential negative influence of cad tools on the formation of students' creativity". Department of Computer Science and Software Engineering, The University of Melbourne.

[56] Yang, M. C., 2005. "A study of prototypes, design activity, and design outcome". *Design Studies,* **26**(6), pp. 649 – 669.

Journal of Mechanical Design. Received January 31, 2017;
Accepted manuscript posted July 13, 2017. doi:10.1115/1.4037251

[57] Viswanathan, V. K., and Linsey, J. S., 2013. "Role of sunk cost in engineering idea generation: an experimental investigation". *J Mech Design,* **135**(12), p. 121002.

[58] Kwasitsu, L., 2004. "Information-seeking behavior of design, process, and manufacturing engineers". *Library & Information Science Research,* **25**(4), pp. 459–476.

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