Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2016
August 21-24, 2016, Charlotte, North Carolina

DETC2016-60407

THE DESIGN FOR ADDITIVE MANUFACTURING WORKSHEET

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ABSTRACT

Additive manufacturing (AM) technologies have become integral to the modern manufacturing process. These roles are filled both in prototyping and production. Many studies have been conducted and lists been written on guidelines for AM. While these lists are useful, virtually none are written in a way that is accessible to novice users of AM, such as Makers. Most guidelines assume the user has extensive prior knowledge of the process, apply to only a few AM technologies, or describe benefits of the technology that novices already know. In this paper, we present a short, visual design-for-additive-manufacturing worksheet for novice and intermittent users. It addresses common mistakes and problems as identified by various expert machinists and additive manufacturing facilities. The worksheet helps designers accurately assess the potential quality of a part that is to be made using an AM process by giving intuitive feedback and indirectly suggest changes to improve a design. The immediate benefit of this worksheet is that it can help to streamline designs and reduce manufacturing errors. We validated it in a high-volume 3D-printing facility (Boilermaker Lab) where users are predominantly novice or intermittent. After the worksheet was implemented in the Boilermaker Lab, both the rate of print failures and reprinted parts fell roughly 40%.

1 INTRODUCTION

Many researchers and industry practitioners have discussed various guidelines for additive manufacturing (AM). However, the guidelines produced to date have a limited usefulness for novice and intermittent users of AM, such as 3D printing. Most guidelines discuss matters already commonly understood by novices (e.g. 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 part). The remaining guidelines tend to be specific for one or two technologies, but are not generalizable.

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

2 BACKGROUND

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 more subtractive methods. However, AM has different limitations than subtractive methods. Therefore, Design for Manufacture (DfM) does not apply in the

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scope of the AM processes [1]. 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 [2, 3]. 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.

The existing literature that refers to itself as "DfAM" can be categorized into 3 groups (see table 1). The first of these groups propose specific design methods that utilize additive manufacturing or describe how DfAM should be part of the entire design process. However, not all of these provide specifics to their proposed methods, instead advocating for more research. The second group researches different approaches for overcoming limitations of AM, such as achieving very small features or reducing the need for support structures. Specific applications now possible using AM often require a tailored process. This can have a significant impact on the outcome of the intended design products. One such example is the ability to closely emulate natural biological systems, which is only now possible due to AM freedoms, but requires a different mode of thinking, even compared to common AM methods [4]. 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. These guidelines are usually intended to be used at any point during design.

TABLE 1. Different versions of "design for additive manufacturing" grouped by focus

Design Methods	AM Technologies	DfAM Guidelines
Diegel et al. [5]	Adam & Zimmer [6]	Adam & Zimmer [6]
Doubrovski et al. [7]	Dede et al. [8]	Ameta et al [9]
Gibson et al. [10]	Garland & Fadel [11]	Diegel et al. [5]
Hague et al. [12]	Gibson et al. [10]	Meisel & Williams [13]
Hague et al. [1]	Gorguluarslan et al. [14]	Panesar et al. [15]
Laverne et al. [2]	Kruth et al. [16]	Pruss & Vietor [17]
Madden & Deshpande [18]	Maute et al. [19]	Rosen [20]
Morton et al. [21]	Meisel & Williams [13]	Rosen [22]
Ponche et al. [23]	Morton et al. [21]	Yang & Zhao [24]
Rosen [4]	Panesar et al. [15]	
Rosen [20]	Ponche et al. [23]	
Rosen [22]	Pruss & Vietor [17]	
Schmelzle et al. [3]	Snyder et al. [25]	
Stankovic et al. [26]	Stankovic et al. [26]	
Vayre et al. [27]	Ulu et al [28]	
Yang & Zhao [24]	Vayre et al. [27]	
	Williams et al. [29]	
	Yim & Rosen [30]	

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 [5, 10, 12], the inclusion of manufacturing features [10], and blunting extreme points [6]. The importance of the 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, whereas 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 softwares by experts. Despite these caveats, the development of DfAM rules or guidelines will continue to show commonalities amongst themselves until the next novel manufacturing or prototyping process is invented and requires a new 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 easier for intermediate users to understand, rather than 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, especially those by Adam and Zimmer [6], tend to be out of the control of many novices using hobby printers, such as controlling the size of the 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. The sheet is designed for novices to additive manufacturing. It is also useful for intermittent or intermediate users as a checklist to go through to validate a design prior to manufacture.

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

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, 10, 15]
	Orientation can have an effect on the surface finish of the part, especially when dealing with rounded features [5,12,13,17]
	The orientation can have an effect on the strength between the horizontal and vertical components (since layers are added in the vertical 'z' direction) [5, 9, 17]
Removal of supports	Removing support structures significantly reduces surface finish and increases the need for post-processing [10]
	Sharp inner edges can reduce the need for support structures as the layers build [6, 12, 17]
Hollowing out parts	When functionally possible, thick walls and hollow interiors can reduce print time [10, 24]
Manufacturing features	While AM does not require undercuts, draft angles, and other process specific considerations, many parts are prototypes that will eventually be manufacturing using traditional processes [10]
Interlocking features	AM processes have a finite build space, and may require that large parts are broken up and joined later with interlocking features [10]
	Ensure that joined/interlocking gap dimensions are minimized to enable robust removal of support structures and ensure small dimensional deviations [6]
Reduction of part count	If the AM part is end-use, the number of parts in an assembly may be reduced [9, 10, 24]
Identification marks	When a company produces many parts, it is easy to lose track of which model is which [10]
Avoid sharp edges	Results in better accuracies; rounding radii correlate with outer radii of simple-curved elements [6]
Round inner edges	Simplify removal of disperse support structures (e.g. powder) [6]
Blunt extreme points	Vertical points blunted parallel to build plane; horizontal points blunted orthogonal to build plane [6]
Short overhang	This ensures robust manufacturability and prevents falling off of layers [6]
Low Island Positions	This will have a significant impact on the build times [6]

After the worksheet was near a final form, we consulted with three high-volume 3D printing labs to see if the worksheet addressed their common concerns. The three labs are 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 FDM 3D printers. The Mech Eng. 3D Printing Lab serves several design courses and the department needs in general. The lab manager, who is also the first expert, has over 20 years of experience in AM and operates 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 addresses 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 will only have one or two AM processes available to them. These considerations are more relevant for expert practitioners who must frequently choose between several AM processes.

3.2 Considerations for the Worksheet

The goal of the worksheet is 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 often will not adopt a new method unless it is very easy to use or required by management. The worksheet is designed to be reminiscent of DfM worksheets. The purpose of this is to aid industry adoption. It is also constrained 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. The 4 categories on 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.

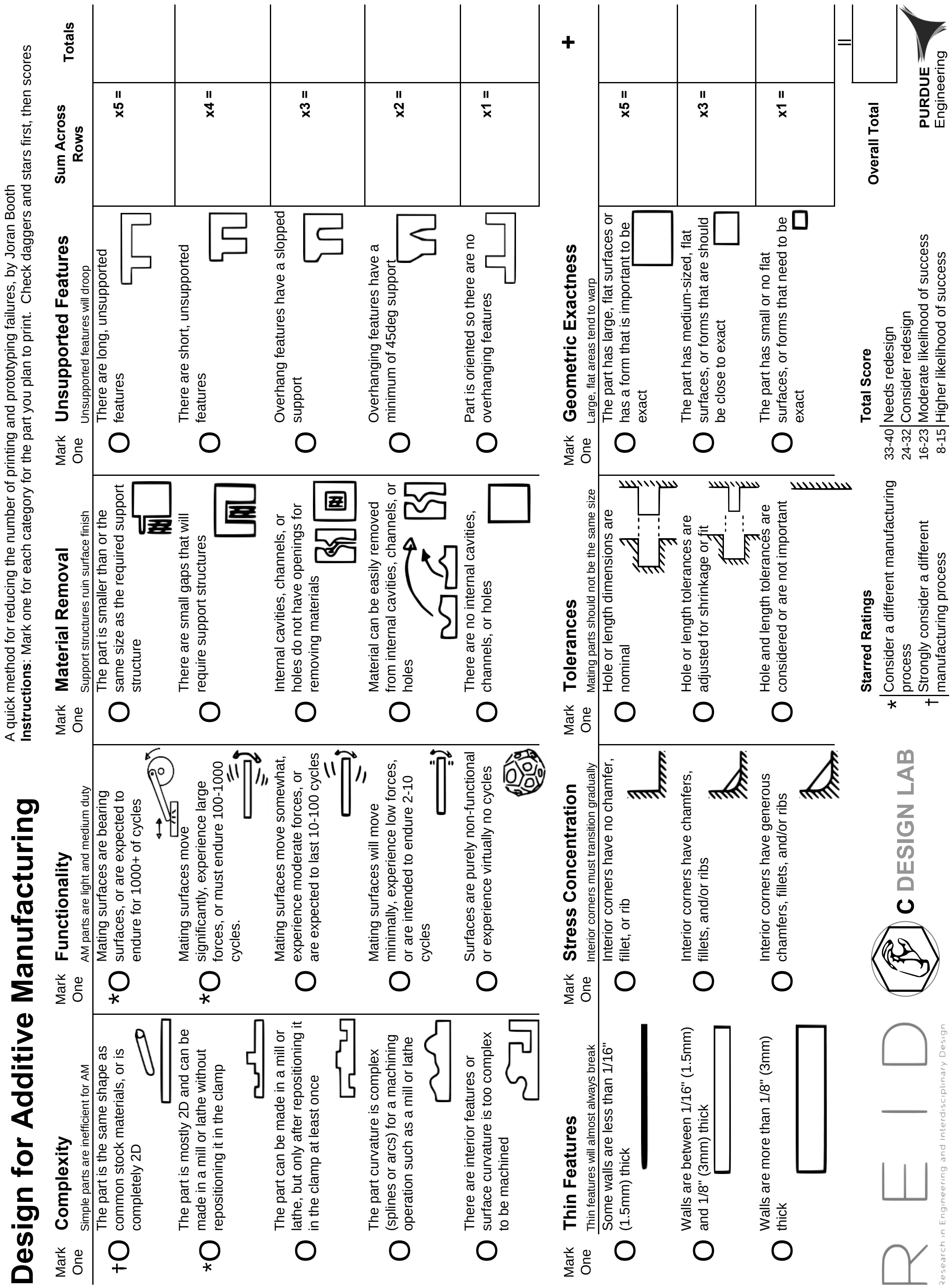


FIGURE 1. The DfAM worksheet is design for novices and intermittent users of additive manufacturing technologies.

The most common problem we saw is that many novices use 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 using metal rods and a bandsaw or simply buying the parts. We also observed many users expected the AM parts to endure a similar number of cycles as a machined part. Material removal and support structures is commonly ignored by novices. For example, many novices using an SLA process create hollow parts but do not include holes to drain fluid from cavities. Additionally, many novices do not consider the poor surface quality left by support structures or the drooping seen in unsupported features.

Our worksheet does not address all of the possible AM considerations. Therefore, it returns a qualitative assessment of risk of failure, rather than directly evaluating the quality of the design. 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 their 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.

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 by reducing the number of iterations a designer must take to create a viable part. Since it would be difficult to track hundreds of designers, and since a laboratory study would necessarily restrict the sample size, we opted for simple metrics to test its effectiveness. The number of iterations for designing a part can be approximated by measuring the number of failed 3D prints and how many files are reprints.

We collaborated with the Boilermaker Lab, a high-volume 3D printing facility which serves the entire Purdue University campus, to measure the effect of the worksheet. We kept logs of print jobs over the period of about a month without using the worksheet. All printers used for the study were Makerbot Replicators, each with 2000+ service hours. 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 later. The data we collected included timestamps, filenames, whether the print failed, whether the DfAM worksheet was used, and the score from the worksheet. We used the filename to track if redesigned parts were resubmitted after an initial print. We should note that we did not discriminate by the cause of the print failure, including common problems such as mechanical failures of the printer or improper leveling of the build plate. This makes our measure rather conservative. 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 using the worksheet, so not all prints from the second month used the worksheet and the log is at times incomplete. Because of this discrepancy, we effective have two separate datasets: the print logs and the worksheet results from Qualtrics.

We wanted to answer two questions with our analysis.

- 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)?

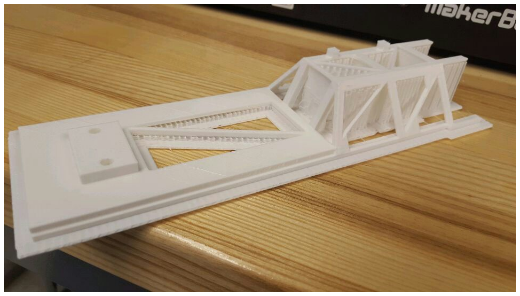
According the survey log from Qualtrics, the number of samples was 102, the median time spent on the worksheet was 2.7 minutes, and the average was 5.4. Three observations were removed due to being longer than four hours because it is almost certain that in these cases the browser was left open.

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 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 is how many parts are reprinted divided by the total. Summary statistics can be found in table 3.

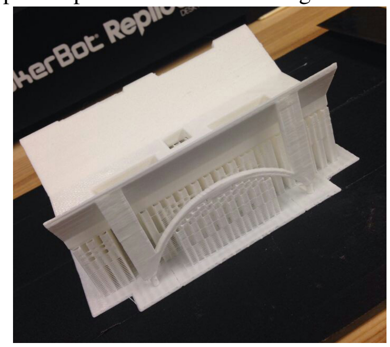
The group which did not use DfAM is much larger than the group which did for two reasons. First, the initial month when we collected data was at the end of the semester when more student projects are being printed, and the month after implementing the DfAM worksheet was in the first month of the new semester with fewer student projects. Second, the worksheet was not consistently applied to the month with the DfAM sheet, and so many of the prints over this period were included in the first group. The sensitivity analysis we present later in this paper uses data from this second month, only.

The overall changes we observed were quite dramatic. The overall number of failures dropped 42% after implementing the

TABLE 4. Examples of prints created after using the DfAM worksheet



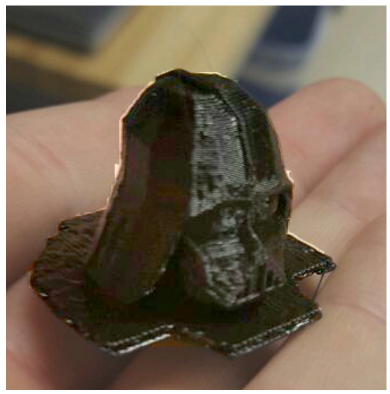
Score = 24



Score = 22

Score = 19

Score = 16



Score = 15

Score = 11

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

	w/o DfAM month 1 & 2	w/ DfAM month 2	Change
n	192	36	
Print fail rate	19.8%	8.3%	42% decrease
Repeat print rate	14.1%	5.6%	39% decrease

	w/o DfAM, month 2 only	w/ DfAM month 2	Change
n	47	36	
Print fail rate	10.6%	8.3%	78% decrease
Repeat print rate	6.4%	5.6%	87% decrease

DfAM worksheet and the rate at which prints needed to be redone decreased 39%. Additionally, there were no third reprints done after the worksheet was implemented, though this may change with more samples. It is important to note that the drop in failure rate is a conservative estimate because we included ALL sources of failure, not just those due to poor part design. The repeat print rate also gives us a better idea of the positive effect this worksheet has on the design cycle.

We conducted a sensitivity analysis with this data as well. It is possible that the data collected before implementing the worksheet had more errors due to it being collected at the end of the semester when students are frantic to complete projects. To test for this, we removed the data from the prior semester and only compared prints with and without the DfAM worksheet during the same time period. We found that the overall print rate was 78% lower when users used the DfAM worksheet, confirming the magnitude of the prior result. We also found that there were a similar number of repeated prints for both conditions over the same period, which suggests that the drop in print rate may not be accurate. However, this highlights the need for further data collection. This alternate test increases confidence that our worksheet is effective for novice and intermediate users of AM.

We also qualitatively compared existing part designs to the ratings the sheet yielded for those parts. We found that the ratings of the sheet are consistent, even at the boundaries between two rating levels. Several examples can be found in table 4.

5 CONCLUSIONS AND RECOMMENDATIONS

In this paper, we present a design for additive manufacturing (DfAM) worksheet designed for improving part quality for novice and intermittent users of additive manufacturing (AM) technologies. The worksheet is unique from 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 a 42% decrease in the print failure rate and a 39% decrease in the reprint rate. These results demonstrate the sheet can help reduce the design cycle for novice and intermediate users.

Based on these results, we recommend using this worksheet in academic and industry environments. Some limitations to this work include sampling from a single university and a potential for inconsistent print logs due to low motivation on the part of lab monitors. While this may limit the potential accuracy of our results, our sensitivity analysis confirms the direction and the significance of the change. Based on these results, future work should 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.

ACKNOWLEDGMENT

We thank the reviewers for their valuable feedback. This work was supported by the Lambert Fellowship through the Mechanical Engineering department at Purdue University and the NSF Award No. 1547134 from CMMI and the Donald W. Feddersen Chair Professorship at the School of Mechanical Engineering. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors thank Dr. Davin Huston, Anna Bowen, and the lab staff at the Boilermaker Lab for helping us collect data and Mike Sherwood, Senthil Chandrasegaran, and Dr. John Starkey for helping develop early drafts of the worksheet. We also appreciate the feedback given by the researchers in the Faboratory, directed by Dr. Rebecca Kramer.

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