A COMPARATIVE STUDY: USING IMMERSIVE VR AND NON-IMMERSIVE VR FOR DESIGN DECISION MAKING IN ADDITIVE MANUFACTURING

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KEYWORDS
Design, Additive Manufacturing, Virtual Reality, DfAM, Immersive

ABSTRACT
Design using Virtual Reality (VR) and Design for Additive Manufacturing (DfAM) are two fields that are growing prevalence in industry. Yet there is little research exploring the advantages of VR to assist DfAM. The following study investigates two types of environments: 1) Immersive Virtual Reality and 2) Non-Immersive Virtual Reality and the abilities presented by each to evaluate parts designed for additive manufacturing. The two environments are compared to assess potential differences in DfAM decision making. This work also explores the effect that geometric complexity can have on DfAM decision making. Participants familiar with DfAM are tasked with evaluating five objects of varied complexity using the Design for Additive Manufacturing Worksheet. Participant scores, evaluation times, and self-reported metrics are recorded and further analyzed. Our findings in this research indicate that as part complexity increases, DfAM scores and evaluation times increasingly differ between Immersive VR and Non-Immersive VR groups. Using self-reported metrics, we also find a potential advantage of using Immersive VR for evaluating DfAM parts.

1 BACKGROUND AND MOTIVATION
In 2017, the global Additive Manufacturing (AM) market size was US$ 8,640 million and is expected to reach US$ 76,900 million by the end of 2025 [1]. Despite its tremendous potential, there are still constraints in AM which have an impact on manufactured parts. Considerations like support generation, minimum feature size, and stress concentrations define the overall quality of a part and may be an oversight to a designer with limited design tools [2]. The proposed research will investigate whether Virtual Reality (VR) (immersive or non-immersive) will benefit designers in Design for Additive Manufacturing (DfAM) decision making. Depending on the results, immersive or non-immersive VR may be proposed as the more effective medium for reducing AM design errors, reducing decision making times, and enhancing confidence in designers. The results of this study will allow DfAM teams in industry to make an argument for or against incorporating VR into their design process. Furthermore, this research can be the basis for studying the use of VR for DfAM and open the door for more in-depth studies.

1.1 Design for Additive Manufacturing
Additive Manufacturing (AM) is an emerging process and is growing prevalence in industry [3]. Accompanying any manufacturing process are design considerations that must be properly utilized to ensure the process is reaching its maximum potential. Design for Additive Manufacturing is a field which explores those considerations as opportunistic and restrictive elements of the process to ensure that a component can (and should) be developed using additive manufacturing [4]. For the purposes of this experiment a DfAM guideline titled “The Design for Additive Manufacturing Worksheet” will be used to evaluate Material Removal, Unsupported Features, Thin Features, Stress Concentrations, and Geometric Exactness [5].

1.2 Design Using Virtual Reality
VR is a broadly used term and may be defined in a variety of ways. For the purposes of this study VR may be defined as Immersive: in which the participant uses a head mounted display (HMD) complete with controllers allowing for full range of motion, and Non-Immersive: where the participant is still interacting with a virtual environment (using computer aided design, or CAD) but is aware of their physical surroundings [6]. VR is currently being used in industry as an educational and design tool and has proven itself do be an effective medium [7]. However, there is no evidence of Immersive VR being used to make DfAM decisions. Currently, parts designed for AM are

evaluated preemptively using computer aided design (CAD) software and build preparation or Slicing software. Parts may also be evaluated physically, but this requires the component to first be made with AM or constructed through other means. Immersive VR may provide an advantage to DfAM evaluation in that the technology combines the efficiency of a CAD environment (evaluating a part before manufacture), with the dexterity and intuitiveness of a physical environment. Immersive VR, if proven to be an effective DfAM decision making tool, may decrease build failures, and decrease the time it takes to evaluate designs.

1.3 Research Objectives

The experiment outlined as follows is meant to explore VR as a decision-making tool in DfAM. Participants will be evaluated on their decisions using either immersive VR (Head mounted display with controllers) or non-immersive VR (monitor and mouse). The primary research questions are as follows.

RQ1: Is there a difference between Immersive VR and Non-Immersive VR in DfAM scoring? Do varying degrees of design complexity play a role?

RQ2: Is there a difference between Immersive VR and Non-Immersive VR in the time it takes participants to make DfAM decisions? Do varying degrees of design complexity play a role?

RQ3: Is there a difference between Immersive VR and Non-Immersive VR in terms of self-efficacy and other self-reported metrics for DfAM?

2 EXPERIMENT: DFAM DECISION DIFFERENCES BETWEEN VIRTUAL REALITY GROUPS

The following experiment was designed to explore the differences in DfAM Scoring, Evaluation Time and Self-Reported Metrics between two virtual reality environments 1) Immersive VR and 2) Non-Immersive VR. This experiment also looks at how varying degrees of shape complexity play a role in these differences. The Immersive VR group utilizes an HTC VIVE [8] comprising of Head Mounted Display (HMD) and controllers allowing for full range of motion of the arms to control the environment. The Non-Immersive VR group utilizes SolidWorks [9], otherwise known as Computer Aided Design Software (CAD) paired with a mouse to control the environment. The actions performed by both groups are kept the same to limit confounding effects.

2.1 Participants

Participants were recruited from a fourth-year design for additive manufacturing course at an accredited university. The participants were familiar with the DfAM worksheet, and the various AM processes. A total of 20 students (18 male, 2 female) participated in the study with ages ranging from 20 to 26 years. While most of the participants were in their senior year (17), the study also included one first-year graduate student and two second-year graduate students. The participants' field of study were Mechanical Engineering (17) and Engineering Design (3). The majority of participants had familiarity with additive manufacturing at an intermediate level (13) or had good skills with additive manufacturing (6) including one at beginner level. The level of participants' familiarity with CAD were Beginner (1), Intermediate (9), and Skilled (10) whereas for VR were Beginner (17), and Intermediate (3). The participants' familiarity with CAD was higher when compared to VR and the majority of them were familiar with additive manufacturing.

2.2 Procedure

Participants were randomly organized into one of two groups: (1) the Immersive VR group or (2) the Non-Immersive VR group. Both the groups comprised of 10 participants each. The Immersive VR group used the HTC VIVE [8] head mounted display and controller to participate in an environment rendered using Unity. The Non-Immersive VR group used a mouse and monitor to participate using SolidWorks [9] as their visualization tool (see figure 1). Each participant was engaged in the study privately with a proctor present.

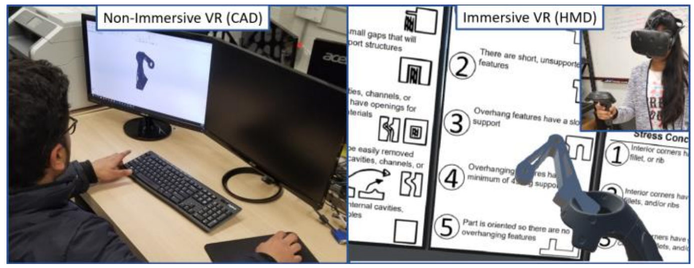

Figure 1: The Participants Were Randomly Organized into the Immersive VR or Non-Immersive VR Group

After consent for participation, each participant completed a pre-test comprising of a background survey and self-efficacy survey. The background survey asked about familiarity and ownership as it relates to additive manufacturing, virtual reality and CAD software. The survey also assigned each participant an anonymous identification code and identified their area of study and year of study. The participant then was asked to fill out a pre-experiment self-efficacy survey (discussed in section 3: Self-Efficacy).

Following completion of pre-test background and self-efficacy questions, the participant was instructed to use either the VR or CAD environment. Before starting the experiment, the participant was provided an overview of the evaluation tool, the necessary controls, and was instructed in how to communicate DfAM scores to the proctors verbally. The participant was then tasked with completing an orientation task, to ensure each participant could recognize the basic features of a model. The participant was presented a 3D extrusion of the letter "A" and was asked to correctly state the number of flat surfaces on the object (the correct answer being 12). The participant was timed for the duration of this orientation task to gain a sense of their performance in their assigned environment, the data was used to note any differences between CAD and VR for the average time it takes to complete a basic task. The participant was then tasked with evaluating five similar objects modeled for the Alcoa Airplane Bearing Bracket Challenge on GrabCAD [10]. These objects were chosen by a committee of DfAM experts and varied in levels of complexity from 1 (least complex) to 5 (most complex) as defined by the DfAM worksheet (see figure 2 below). The participant was independently introduced to one object at a time randomly to eliminate comparison and ordering effects [11]. For each object the participant was responsible for reporting scores for the restrictive elements as defined in the DfAM worksheet (Material Removal, Unsupported Features, Thin Features, Stress Concentrations, and Geometric Exactness). The participant was timed for each object evaluation. After evaluating each of the five objects, participants then took a post-test consisting of the same self-efficacy questions discussed earlier, a demographics survey that requested gender, age, and ethnicity, followed by a feedback survey to improve upon the experiment in the future.

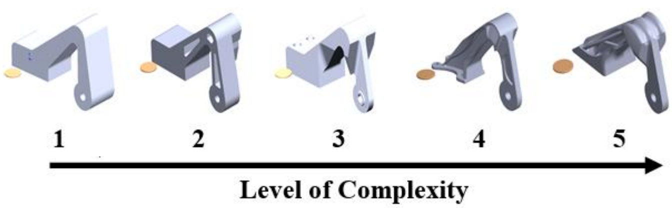

Figure 2: Shape Complexity Levels 1 to 5 of brackets designed for the Alcoa GrabCAD Challenge

3 METRICS

Multiple metrics were used to assess the impact of immersive and non-immersive VR use. A pre-post survey was developed to assess self-efficacy among the participants. The participants' DfAM scores were also measured and analyzed along with the evaluation time.

3.1 Self-Efficacy

Self-efficacy was defined by Bandura in 1994 as a person's self-perceived ability to complete a task [12]. Different levels of self-efficacy can predict how a person may respond to stress and failure. They can also be a good estimator of how likely they will be in achieving success. Two main types of self-efficacy exist: process self-efficacy and outcome self-efficacy [13]. Process self-efficacy involves questions that discuss the general process steps likely to result in successful outcomes. Outcome self-efficacy involves rating outcome specific questions. For this study, a two-part self-efficacy assessment was constructed to measure self-efficacy in the generalized DfAM as well as self-efficacy of experiment-specific tasks and outcomes. The first part of the survey was based on Carberry's verified self-efficacy assessment of engineering design [14]. The survey is a process self-efficacy assessment that looks at well-established engineering design process steps. Due to the AM focus of this study, the assessment was revised to apply to DfAM. These modified design process steps can be viewed in figure 3. The steps were to identify a need to use AM, to develop design solutions using AM, to select the best possible design for AM, to evaluate a part for AM, and to redesign a part for AM. The participants were then asked to assess the following four task-specific concepts of interest for each step: confidence, motivation, anticipated level of success, and anxiety. These four concept categories were chosen to help clarify the more general process steps. They have been shown to correlate with self-efficacy (confidence) [14]. The second part of the survey was developed as an outcome self-efficacy assessment, with tasks pertaining to the specific experiment tasks involving restrictive areas of DfAM. These tasks can be seen listed in figure 3. The tasks were to evaluate a part for material removal, unsupported features, thin features, concentration, and geometric exactness. Due to the specific nature of these tasks, the only concept category of interest was confidence. The survey instructed participants to rate the specific concept of interest for each step or task on a scale of 0 to 100 with increments of 10. This scale was chosen because it gives a more sensitive, increased performance prediction [15]. Bandura's Guide for Constructing Self-Efficacy Scales was used in developing the self-efficacy survey as well [16]. This self-efficacy survey was given to students pre- and post-experiment to measure any changes in self-efficacy due to participation in the experiment. The data from this survey was collected to assess the task-specific self-efficacy relating directly to the experiment (discussed in section 7: Conclusion and Future Work).

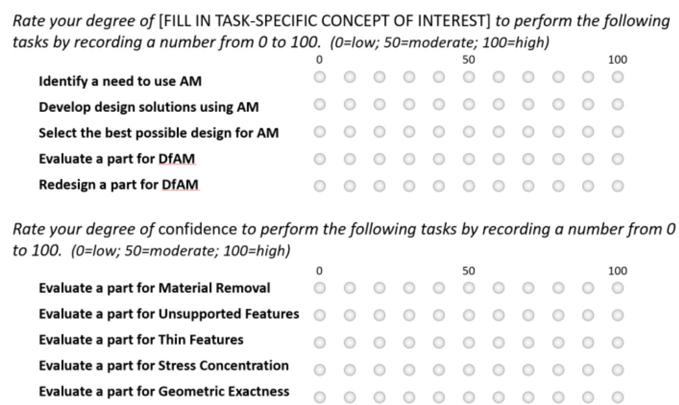

Figure 3: Two-Part Self-Efficacy Survey Tasks

3.2 DfAM Scoring

Participants were instructed to score five different objects using the restrictive aspects of the DfAM worksheet (see Appendix A1). The DfAM worksheet was designed to assist novice and intermediate designers to improve AM part quality. The worksheet has demonstrated a reduction in "bad parts" designed for AM by requiring designers to consider 8 aspects: Complexity, Functionality, Material Removal, Unsupported Features, Thin Features, Stress Concentration, Tolerances and Geometric Exactness [5]. This experiment only requires that participants evaluate each part using the restrictive aspects of the DfAM worksheet: Material Removal, Unsupported Features, Thin Features, Stress Concentration, and Geometric Exactness (see Appendix A2). Complexity is not included in evaluation because it is one of our independent variables, AM experts selected five different objects, one for each level of complexity as defined by the DfAM Worksheet, for the participants to evaluate. Functionality was not included in the evaluation because all parts selected were designed to perform the same task, so there would not be a large variation in scores for this metric. Tolerances were not considered in evaluation because the parts selected were not presented as an assembly, they were evaluated individually, and therefore tolerances are not relevant. The remaining metrics, Material Removal and Unsupported features were scored from 1 to 5 in five steps (1, 2, 3, 4, and 5). Thin Features, Stress Concentration, and Geometric Exactness were also scored from 1 to 5 but in 3 steps (1, 3, and 5).

A score of 1 for Material Removal means the part will likely be the same size as the structures supporting it, and a score of 5 means the part has no internal cavities or holes requiring support material. A score of 1 for Unsupported Features means the part will have long unsupported features, and a score of 5 means that the part may be oriented so there are no overhanging features. A score of 1 for Thin Features means that some walls of the part are less than 1.5mm thick, and a score of 5 for Thin Features means that walls are more than 3mm thick (participants are presented with a model of a penny designed to be 1.5mm thick for them to reference during this part of the evaluation). A score of 1 for Stress Concentration means that the interior corners of a part have no chamfer, fillet, or rib, and a score of 5 for Stress Concentration means that the interior corners have generous chamfers, fillets or ribs. A score of 1 for Geometric Exactness means that the part has large flat surfaces, and a score of 5 means that the part has small or no flat surfaces. The total scores for each object for each participant were tallied and later used for data analysis.

3.3 Evaluation Time

Participants were also timed during the study. When a new object was presented to them, the timer was started and the timer was not stopped until the participant completed DfAM evaluation for the object. The participant would then be presented with a new object and the process would repeat. Time was recorded in seconds for each object for each participant and was later used in data analysis.

4 DATA ANALYSIS

10 participants were randomly assigned to the Immersive VR group, and 10 participants were randomly assigned to the Non-Immersive VR group. The final DfAM scores and times were tallied and compared using a two-way mixed analysis of variance (ANOVA). The dependent variables were DfAM score and design evaluation times, the independent variables were design complexity and evaluation environment (Immersive VR or Non-Immersive VR). Machlys test of sphericity indicated that the assumption of sphericity was met for the two-way interaction for both time and score (p=0.225, p=0.355). Using a two-way ANOVA we planned to look into what interactions occur for scores and evaluation time when varying degrees of object complexity are introduced. An independent samples T-Test was later run to look at simple main effects as well. A combined average of the five AM design statements was used to determine self-efficacy, motivation, outcome expectancy, and anxiety for DfAM.

4.1 RQ1: Is there a difference between Immersive VR and Non-Immersive VR in DfAM scoring? Do varying degrees of design complexity play a role?

Two-way interactions were evaluated based on whether the participant was assigned to the Immersive or Non-Immersive VR group. This allowed us to evaluate differences in DfAM scoring according to group and object complexity (see figure 4.) It was found that there were overall no significant interaction effects between evaluation environment and complexity on DfAM scoring (p=0.188).

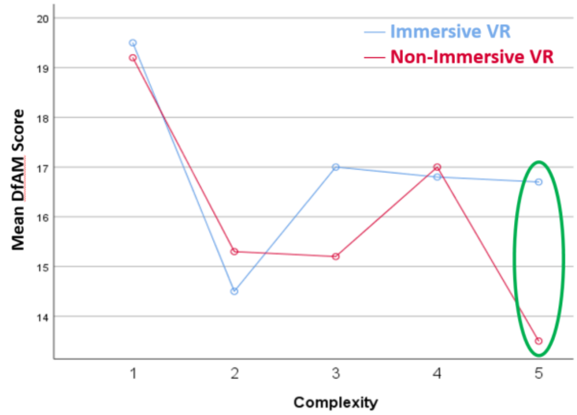

Figure 4: Estimated Marginal Means of DfAM Score

Given that a significant interaction was not found, simple main effects were then evaluated using an independent samples t-test at each level of complexity. A significant difference in DfAM score was found as indicated in Table 1 between groups for the most complex object (p=0.007).

Table 1: Independent Samples t-test for DfAM Score

Complexity	Mean VR (Score)	Mean CAD (Score)	Sig.
1	19.5	19.2	0.825
2	14.5	15.3	0.604
3	17	15.2	0.303
4	16.8	17	0.886
5	**16.7**	**13.5**	**0.007**

4.2 RQ2: Is there a difference between Immersive VR and Non-Immersive VR in the time it takes participants to make DfAM decisions? Do varying degrees of design complexity play a role?

Two-way interactions were again evaluated based on whether the participant was assigned to the Immersive or Non-Immersive VR group. This similarly allowed us to evaluate differences in evaluation time according to group and object complexity (see figure 5). Again, it was found that there were overall no significant interaction effects between evaluation environment and complexity on evaluation time (p=0.431).

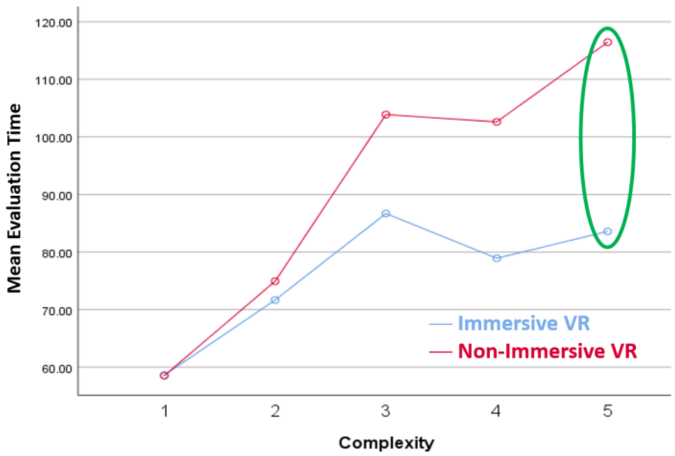

Figure 5: Estimated Marginal Means of Evaluation Time

An independent samples t-test at each level of complexity was run to evaluate simple main effects. Table 2 shows a significant difference in evaluation time was found between groups for the most complex object (p=0.006).

Table 2: Independent Samples T-Test for Evaluation Time

Complexity	Mean VR (Time in Seconds)	Mean CAD (Time in Seconds)	Sig.
1	58.61	58.52	0.995
2	71.66	74.93	0.772
3	86.69	103.99	0.433
4	78.92	102.62	0.206
5	**83.58**	**116.46**	**0.006**

4.3 RQ3: Is there a difference between Immersive VR and Non-Immersive VR in terms of self-efficacy and other self-reported metrics for DfAM?

The results for the DfAM self-efficacy pre and post tests were plotted. No significant differences were found between pre and post scores, or between Immersive VR and Non-Immersive VR groups (see figures 6-9). There was a notable difference for anticipated success where the Immersive VR group (VR) had a slightly larger increase than the Non-Immersive VR group (CAD). There was also a notable difference for anxiety, where the Non-Immersive VR group (CAD) had a slightly larger increase than the Immersive VR group (VR).

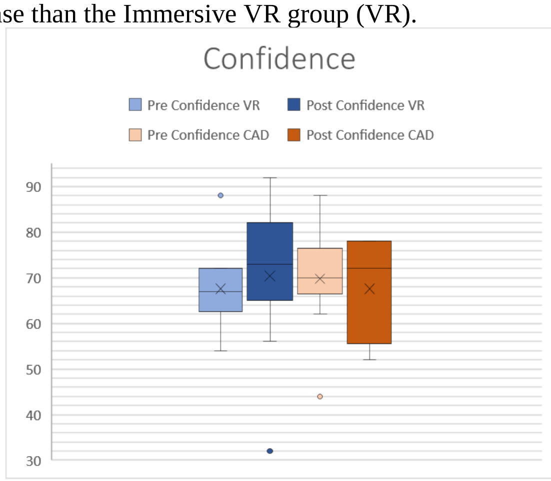

Figure 6: Self-Reported Confidence in Evaluating Parts for DfAM

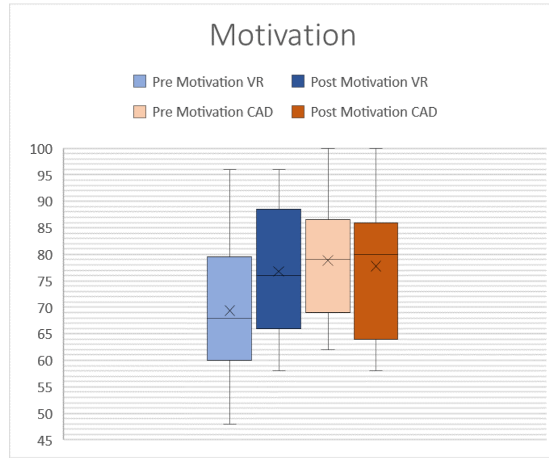

Figure 7: Self-Reported Motivation in Evaluating Parts for DfAM

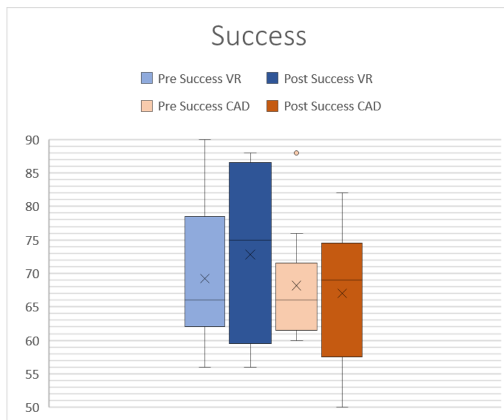

Figure 8: Self-Reported Anticipated Success in Evaluating Parts for DfAM

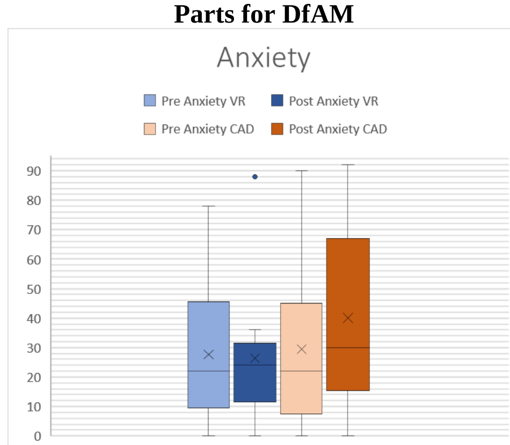

Figure 9: Self-Reported Anxiety in Evaluating Parts for DfAM

5 DISCUSSION

This experiment was conducted to uncover differences in DfAM evaluation as a result of object complexity (1 through 5) and evaluation environment (Immersive VR and Non-Immersive VR). Research questions RQ1, RQ2 and RQ3 are further discussed using the data analysis to support claims.

RQ1: Is there a difference between Immersive VR and Non-Immersive VR in DfAM scoring? Do varying degrees of design complexity play a role?

Yes, the different environments do have an effect on DfAM scoring, and yes, complexity does play a role. While we do not see a significant interaction using the two-way mixed ANOVA, we can still see larger differences in scores as complexity increases (see figure 4). At an object complexity of level 1, both groups give relatively the same score. This makes sense; since the object is not very complex there are not many intricate features to be identified. It doesn't necessarily matter what evaluation environment is used as the evaluation is so simple. In contrast, for the most complex object, the DfAM scores were found to be significantly different between groups. This again makes sense, if an object is extremely complex a participant using Immersive VR may be able to identify features that the other group cannot and vice versa. It was found that the group using SolidWorks gave significantly lower DfAM scores than the group using the HTC VIVE; a lower DfAM score suggests that the component is more likely to be a successful candidate for AM. However, this result should not be used to make any conclusions just yet; a better way to look at these scores would be to compare them to scores given by DfAM experts to see which group is more accurate in their evaluation. This proposed method is later mentioned in section 7: Conclusion and Future Work.

In short, these results imply that when evaluating simple objects, it does not necessarily matter which evaluation environment is available, the DfAM scores will be the same. But with increasing levels of complexity, the evaluation environment will matter, and the designer should consider which evaluation environment will give them the advantage.

RQ2: Is there a difference between Immersive VR and Non-Immersive VR in the time it takes participants to make DfAM decisions? Do varying degrees of design complexity play a role?

Yes, and yes again. Similar to RQ1, the time is relatively similar for the least complex object. As object complexity increases, the overall evaluation time increases, and the evaluation time between groups grow further and further apart (see figure 5). A significant difference was found between groups for the most complex object, where the Immersive VR group took less time to evaluate. This was surprising to find; we assumed that the Non-Immersive VR (CAD) group would take less time for more complex objects because of the higher experience with the environment (reported in section 2.1).

These findings indicate that Immersive VR may have an advantage over Non-Immersive VR for evaluating complex DfAM parts. Evaluation of complex parts using Immersive VR will be faster, saving design review teams time. However, it is still not known if that faster evaluation will be a more accurate evaluation as well, this issue is further discussed in section 7.

RQ3: Is there a difference between Immersive VR and Non-Immersive VR in terms of self-efficacy and other self-reported metrics for DfAM?

There were two notable differences found between groups for self-efficacy/other self-reported metrics. The Non-Immersive VR group had a slightly larger increase in anxiety for evaluating DfAM parts, and the Immersive VR group had a slightly larger increase in anticipated success for evaluating DfAM parts. Those using Immersive VR to evaluate DfAM parts will, as a result, feel slightly more likely to succeed and less anxious in their abilities.

6 LIMITATIONS

In designing this experiment, we tried to minimize anticipated difficulties. We anticipated the potential of ordering bias [11], so we randomized the order of the objects for each participant. We also anticipated comparison bias [11], so we designed the experiment to prevent participants from viewing more than one object at a time. The participant's familiarity with the systems (CAD or VR) could have also led to bias. We included a software demonstration in the beginning of the experiment to ensure each participant felt comfortable in their environment and mitigate this bias.

Another difficulty we anticipated was the time required for performing the experiment. Participants had roughly 20 minutes to evaluate 5 DfAM parts before the next participant was scheduled to come in. The participants of course were not given a time constraint, they were told to take as much time as they need for evaluation; but we also didn't want to keep other participants waiting. To try to mitigate this, we tested the experiment with DfAM novices, had multiple computers available for survey forms/data collection, and prepared to overlap the survey portions of the experiments. We also had a contingency plan in place to reschedule participants to a later time slot as a last resort if we ran behind schedule. Participants were also warned if they were late to the experiment then the proctors may deny their participation, this ensured participants arrived in a timely manner to keep the experiment on schedule.

7 CONCLUSION AND FUTURE WORK

The experiment results indicated a significant difference in DfAM scores between groups for the most complex object. It was also found that Immersive VR had a significantly faster evaluation time for the most complex object. Finally, it is possible that Immersive VR can improve participants anticipated success and have a lesser effect on anxiety for DfAM part evaluation. Most notably, we are seeing that as object complexity increases, the results between Immersive and Non-Immersive VR grow apart, suggesting that this research should be further explored with more complex objects.

Future work will require more in-depth examination of potential ordering and comparison effects, the comparison of participant DfAM scores to scores given by DfAM professionals, and additional tests with self-efficacy data to uncover any significance. Comparing DfAM scores to that of DfAM professionals is arguably the most important step in moving this research foreword. This research has highlighted that for complex objects there is a significant difference in evaluation time and DfAM score, but we do not know the accuracy of the tallied scores. The group with the lower evaluation time, Immersive VR, were they faster *and* more accurate? Or is it possible that they were less accurate *because* they performed the task faster? These are very important questions to answer to make the argument for or against VR as a DfAM tool.

Experiment modifications may also be considered such as recording print orientations, recording participants "thinking out loud", and restructuring the orientation task. The orientation task mentioned in Section 2.2 proved to be confusing for many participants making the data invalid. An orientation task that is easier to understand/explain is recommended for future work.

ACKNOWLEDGMENTS

We would like to acknowledge the support of Dr. Christopher McComb and Dr. Timothy Simpson for their consultation. We would also like to thank Dr. Nicholas Meisel for his consultation and for allowing us to work with his DfAM students for our experiment. Additional thanks to members of the Made By Design Lab (MBDL) and the Engineering Design and Optimization Group (EDOG) for their support with the experiment and analysis.

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APPENDIX

A1: DESIGN FOR ADDITIVE MANUFACTURING WORKSHEET

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**
†O	The part is the same shape as common stock materials, or is completely 2D	*O	Mating surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles	O	The part is smaller than or the same size as the required support structure	O	There are long, unsupported features	x5 =	
*O	The part is mostly 2D and can be made in a mill or lathe without repositioning it in the clamp	*O	Mating surfaces move significantly, experience large forces, or must endure 100-1000 cycles.	O	There are small gaps that will require support structures	O	There are short, unsupported features	x4 =	
O	The part can be made in a mill or lathe, but only after repositioning it in the clamp at least once	O	Mating surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles	O	Internal cavities, channels, or holes do not have openings for removing materials	O	Overhang features have a slopped support	x3 =	
O	The part curvature is complex (splines or arcs) for a machining operation such as a mill or lathe	O	Mating surfaces will move minimally, experience low forces, or are intended to endure 2-10 cycles	O	Material can be easily removed from internal cavities, channels, or holes	O	Overhanging features have a minimum of 45deg support	x2 =	
O	There are interior features or surface curvature is too complex to be machined	O	Surfaces are purely non-functional or experience virtually no cycles	O	There are no internal cavities, channels, or holes	O	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		**+**
O	Some walls are less than 1/16" (1.5mm) thick	O	Interior corners have no chamfer, fillet, or rib	O	Hole or length dimensions are nominal	O	The part has large, flat surfaces or has a form that is important to be exact	x5 =	
O	Walls are between 1/16" (1.5mm) and 1/8" (3mm) thick	O	Interior corners have chamfers, fillets, and/or ribs	O	Hole or length tolerances are adjusted for shrinkage or fit	O	The part has medium-sized, flat surfaces, or forms that are should be close to exact	x3 =	
O	Walls are more than 1/8" (3mm) thick	O	Interior corners have generous chamfers, fillets, and/or ribs	O	Hole and length tolerances are considered or are not important	O	The part has small or no flat surfaces, or forms that need to be exact	x1 =	

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Overall Total

REID
Research in Engineering and Interdisciplinary Design

C DESIGN LAB

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

PURDUE Engineering

A2: DESIGN FOR ADDITIVE MANUFACTURING WORKSHEET (ALTERED FOR EXPERIMENT)