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STUDYING CHANGES TO THE ADDITIVE MANUFACTURABILITY OF DESIGN SOLUTIONS WHEN PREPARED AND SIMULATED IN IMMERSIVE VIRTUAL REALITY

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ABSTRACT

Solving problems with additive manufacturing (AM) often means fabricating geometrically complex designs, layer-by-layer, along one or multiple directions. Designers navigate this 3D spatial complexity to determine the best design and manufacturing solutions to produce functional parts, manufacturable by AM. However, to assess the manufacturability of their solutions, designers need modalities that naturally visualize AM processes and the designs enabled by them. Creating physical parts offers such visualization but becomes expensive and time-consuming over multiple design iterations. While non-immersive simulations can alleviate this cost of physical visualization, adding digital immersion further improves outcomes from the visualization experience. This research, therefore, studies how differences in immersion between computer-aided (CAx) and virtual reality (VR) environments affect: 1. determining the best solution for additively manufacturing a design and 2. the cognitive load experienced from completing the DfAM problem-solving experience. For the study, designers created a 3D manifold model and simulated manufacturing it in either CAx or VR. Analysis of the filtered data from the study shows that slicing and printing their designs in VR yields a significant change in the manufacturability outcomes of their design compared to CAx. No observable differences were found in the cognitive load experienced between the two modalities. This means that the experiences in VR may influence improvements to manufacturability outcomes without changes to the mental exertion experienced by the designers. This presents key implications for how designers are equipped to solve design problems with AM.

Keywords: additive manufacturing, design for additive manufacturing, virtual reality, design problem solving, 3D printing simulation

1. INTRODUCTION

Organizations competing against sustainability, cost, and time-to-market requirements are adopting advanced manufacturing technologies to address their engineering challenges. Additive manufacturing (AM) offers a competitive advantage to these groups and is thus increasingly being used to fabricate end-use parts[1]. However, such organizational adoption of AM needs designers who can specifically produce parts that take advantage of AM while accounting for its limitations[2]. This is because parts designed for AM can incorporate unique geometric and material complexities, distinguishing them from parts created using subtractive and formative manufacturing processes[3,4]. There is a shortage of designers with a thorough understanding of DfAM and AM process concepts to meet the demand for AM[5–8]. This deficit limits AM adoption within organizations, overcoming which is, therefore, crucial to innovate with AM[9,10]. For this purpose, designers must be equipped with design and process-centric AM knowledge for the range of AM processes and materials. This knowledge is essential to cultivating the skill necessary to produce functional and manufacturable parts while minimizing failures, defects, and functional errors. To acquire this knowledge, designers must experience solving problems with AM by visualizing the fabrication of their designs to hone their design for AM (DfAM) intuition. Therefore, this research introduces a DfAM problem and studies how such visualization affects a designer's design and manufacturing decisions for AM.

Visualizing the form, scale, aesthetics, and ergonomics of a solution is a fundamental step in checking its viability during design processes[11,12]. With designs for AM, the solution's manufacturability is also important, making it crucial to visualize and incorporate manufacturing considerations in DfAM processes. The experience of actively working with 3D printers to fabricate functional parts is necessary to visualize the benefits and limitations of AM technologies[13–16]. Doing so for the range of AM processes fosters a breadth of technical competency and design intuition for AM, essential to innovating with AM[3,17,18]. Although processes like material extrusion (ME) are quite accessible, others like powder bed fusion (PBF) are not due to their inherently high cost, safety, and

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infrastructural requirements[19,20]. This limits the hands-on experiences designers can have with AM systems, thus limiting their opportunity to cultivate problem-solving skills for AM. Even with physical access to AM systems, low manufacturing speeds limit rapid learning and problem-solving with AM[21,22]. There is a need for accessible alternatives that support visualizing and testing designs for AM to rapidly cultivate problem-solving skills for AM. Working with virtualized AM systems offers such alternatives, motivating an investigation into the use of virtual experiences for DfAM problem-solving.

Virtual manufacturing methods, such as computer simulations, data models, and other digitally fabricated resources, help visualize and test products and manufacturing processes before their physical realization[23–25]. Science and engineering have historically leveraged simulations, games, and digital twins using computer-aided technologies (CAx) for this purpose[26–29]. Past work in virtualized AM also shows potential in demonstrating the 3D printing outcomes of different designs to offer such insight[30–32]. Although non-immersive virtual simulations have historically been used during problem-solving as alternatives to physical learning and decision-making[33,34], adding immersion shows the potential for improved learning and communication outcomes, key requirements for effective problem-solving[35–38]. This is because modalities like virtual reality (VR) with enhanced immersion and presence influence 3D perception[39] to improve design and engineering experiences and their experiential outcomes[40–44]. Past work even shows promise in specifically teaching design and process-centric AM concepts using VR[30,31,45]. However, no known work investigates how differences in immersion affect the application of such conceptual knowledge on the outcomes of a DfAM problem-solving experience. To address this gap, this research studies how designers additively manufacture their solution to a design problem in either a CAx or VR environment.

Designers must be equipped with digital experiences to visualize their solutions and rapidly solve design problems with AM. To do so, digitally immersive and non-immersive experiences, offered by VR headsets and flat-screen computers respectively, must be examined within AM contexts. Knowledge of their benefits and limitations will inform the design of digital experiences, tailored to enhance designers' problem-solving abilities with AM. The goal of this research is to, therefore, study the use of immersive VR and non-immersive CAx in AM problem-solving. Problem-solving with AM, however, employs two different types of rationalization: 1. applying DfAM knowledge to generate a solution, and 2. identifying the best approach to manufacture the solution. The latter specifically requires designers to assess the best orientation to additively manufacture their solutions. Therefore, this research first tasks designers with generating a 3D model to solve a DfAM problem. They must then evaluate the solution's manufacturability by determining the best print orientation for it in a CAx or VR environment. The effects of immersion on the change in manufacturability outcomes of the designs and the cognitive load experienced by the designers are studied. Section 3 describes the study methodology used to address the research questions proposed in Section 2. Findings from the data analysis are then presented in Section 4 and discussed with their implications in Section 5. Lastly, Section 6 summarizes the collective contributions of this research and its limitations for future work.

2. RESEARCH QUESTIONS

This research aims to investigate how immersion affects how designers manufacture a design with AM by determining the best orientation for fabrication in a CAx or VR environment. The study also observes how cognitive load varies between the two modalities during the problem-solving experience. These research questions guide this investigation:

RQ 1. *How do differences in immersion between CAx and VR affect the change in manufacturability outcomes of a solution designed for AM?*

This research question identifies the effects of immersion on the change in manufacturability outcomes when problem-solving with AM. Specifically examined are 1. the time spent identifying the best solution, 2. the time taken for print completion, 3. the support material used for the print, and 4. a manufacturability score for the designs (based on the print time and support material used). Compared to the CAx problem-solving, it is hypothesized that the manufacturability evaluations in VR will yield higher scores, faster prints, and lower material usage. However, no significant differences between the two modalities are expected for the time spent identifying the best solution. Such trends are hypothesized due to expected enhancements in spatial perception and reasoning within immersive modalities[41,42,46,47].

RQ 2. *How do the differences in immersion between CAx and VR affect the cognitive load experienced from manufacturing of a solution designed for AM?*

This research question identifies the effects of immersion on the cognitive load experienced from designing and manufacturing a 3D model to solve a design problem with AM. Specifically examined is the self-reported cognitive load experienced by the designers. Compared to the CAx experience, it is hypothesized that the VR experience will generally yield lower reported cognitive load values. It is expected that the effort required to perform manufacturability evaluation operations for a design, and thus the cognitive load, changes due to the change in immersion. Specifically, evaluations within modalities that require low effort will yield lower reported cognitive load than those that require high effort[48–51]. Such variation in effort is expected to arise due to differences in immersion, the perceived complexity of the designs, and the required engagement with the designs.

3. METHODOLOGY

Participants completed the steps illustrated in Figure 1 on an online Qualtrics survey for the designed study. This includes engaging with the questionnaires, instructions, and the CAx and VR AM environments. No personal or identifiable information was collected from the participants. Completing the survey corresponded to opting in for the study; not doing so was registered as *opting out* of the study. Participant data was deleted accordingly as per the approved Internal Review Board (IRB) protocol.

The remainder of this section describes the steps completed by the participants for the designed study as shown in Figure 1. Section 3.1 describes the pre-study procedure, Section 3.2 the design of the virtual AM environment, and Section 3.3 the details of the DfAM problem. Lastly, Section 3.4 describes the measurement of cognitive load after the DfAM problem-solving exercise.

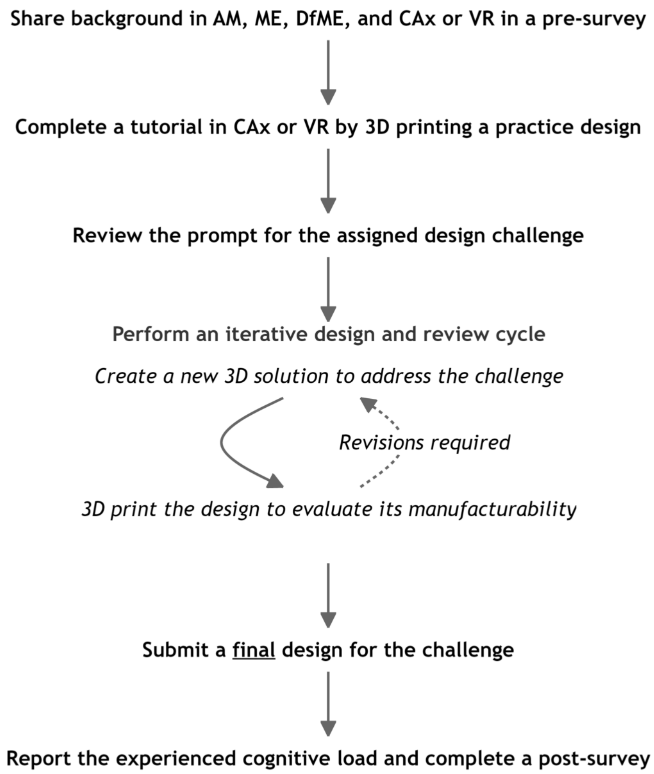


FIGURE 1: Illustrating the order of steps completed by the participants in the CAx and VR conditions for the designed study

3.1 Pre-study procedure

Participants in this study were second and third-year undergraduate students from an engineering design methodology course at an R1 university. They were reminded of their rights and options as per IRB protocol before beginning the study. Students who *opted in* were directed to an online Qualtrics survey to begin the study. The survey's hidden algorithm balanced assignments evenly between the two conditions: CAx or VR. This means that the participants were distributed before the study began to ensure an equal number of participants in each condition. Once assigned to a condition, participants first shared their knowledge of AM in the survey. This included their general experiences with AM and their specific experiences with the ME and DfME. This data helped check for prior knowledge in the statistical analysis of the measured outcomes in the study. Knowledge in AM, ME, and DfME was recorded on the following 5-point Likert scale:

1. I have never heard or learned about this topic before this
2. I have some informal knowledge on this topic
3. I have received some formal knowledge on this topic
4. I have received lots of formal knowledge on this topic
5. I am an expert on this topic

Next, participants described their proficiency with their assigned modality, i.e., with CAx and VR. Specifically, they were prompted to share their proficiency in working with or interacting with 3D models. Participants likely had much more experience working with CAx tools than with VR tools. Therefore, it was important to measure, acknowledge, and then balance any differences in technological proficiency before comparing the measured outcomes between CAx and VR. Proficiency in CAx and VR was recorded on this 5-point Likert scale:

1. I have never worked with 3D in this modality before this
2. I am slightly comfortable working with 3D in this modality
3. I am comfortable working with 3D in this modality
4. I am extremely comfortable working with 3D in this modality
5. I am an expert on working with 3D in this modality

Upon completing the questionnaire, participants were informed about their assigned modality for the first time. Those assigned to the CAx condition were directed to the AM environment via a link on their computers. Those in the VR condition were each given a Meta Quest headset and controllers and directed to the AM simulation on the Meta Quest Browser app. Then, participants immediately proceeded to the tutorial: a practice experience designed to familiarize them with their assigned modality and the AM environment described in Section 3.2. To familiarize themselves with this new AM environment, participants manufactured one example design during the tutorial. They manufactured the design in various orientations to visualize the outcomes for each orientation. After completing the tutorial, participants were presented with the DfAM problem described in Section 3.3.

3.2 The virtual AM environment

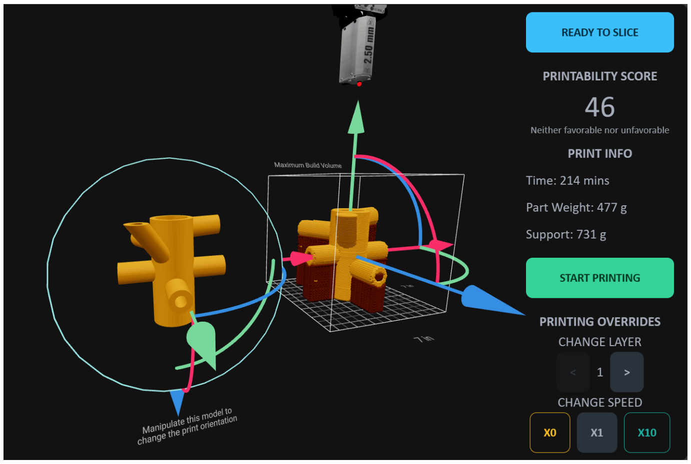
The virtual AM environment used in this research was based on standard 3D printing slicer programs that inform designers about the printing outcomes of their designs. The outcomes in these slicer programs include the time to print completion, the amount of support material used for the print, etc. As such, the virtual AM environment replicated the process of slicing and printing a 3D model for AM to help designers visualize the manufacturability of their designs. The AM environment included four key features to aid designers in visualizing the AM process and assessing the manufacturability of their designs:

1. A 3D model of the solution submitted by the participants
2. A sliced counterpart of the solution in the chosen orientation
3. An extruder to emulate the layer-by-layer printing process
4. A graphical interface to slice models, control the printer, and view the manufacturing outcomes

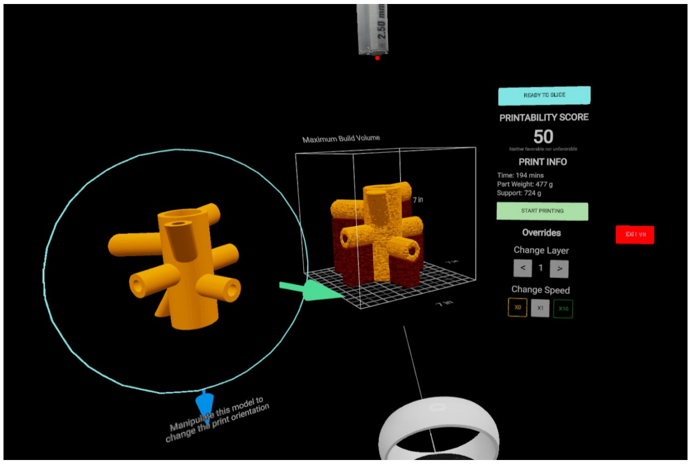
The designed environments were developed by the authors using openly-accessible software and libraries. The 3D web application was distributed online and accessed by the participants using their web browsers. WebXR technology was used to introduce VR capabilities, and the libraries used to create the 3D environment were the Poimandres react libraries[1] powered by

[1]Website for react libraries: https://github.com/pmndrs/website

three.js[2]. All the VR experiences were tested on the Meta/Oculus Quest 2 and HTC Vive devices only. The open-source Cura slicing engine was used to slice the 3D models submitted by participants. This slicing was run directly in the browser using a WebAssembly version of the engine[3]. This engine calculated the print outcomes of the designs every time designers submitted a new design or changed the orientation and re-sliced the 3D model. Running the engine behind the scenes allowed the participants to quickly visualize the manufacturability of their designs in real-time in the 3D environment, similar to standard print slicer programs.



(a) CAx 3D printer



(b) VR 3D printer

FIGURE 2: Presenting the design of the AM environments for each condition which included the designed artifact, a 3D printer, and a graphical interface to use the printer and view the print outcomes

To ensure that the DfAM exercise was similar across the conditions, the environments were designed identically as shown in Figure 2. Free interaction with a design and its environment was permitted to encourage intuitive exploration of the designs. This means that participants were not restricted to a specific orientation or view of the design and were encouraged to explore the design in multiple orientations. As such, typical engagement included picking up, rotating, and moving the models to get a good view of the design. Scaling or modifying the 3D geometry in the environment was not permitted. This ensured that the designs, and their features, were manufactured at their intended scale, yielding an identical comparison of outcomes between the modalities.

3.3 The DfAM problem

Participants were tasked with designing at least one 3D model for a manifold that channels fluid flow from various inlets into a single outlet. No limit was placed on the number of designs that could be created. Participants were also free to use the CAD software they were most comfortable with to design their solution (most used Solidworks). The design problem imposed a *design* and *non-design space*, as visualized in Figure 3. The specific design requirements for the manifold were as follows:

- The manifold design must not exceed the 5 x 5 x 5 cubic inch design space
- The wall thickness of each channel must uniformly be at least 0.25 inches
- Each inlet must be directly connected to a channel that leads to the outlet

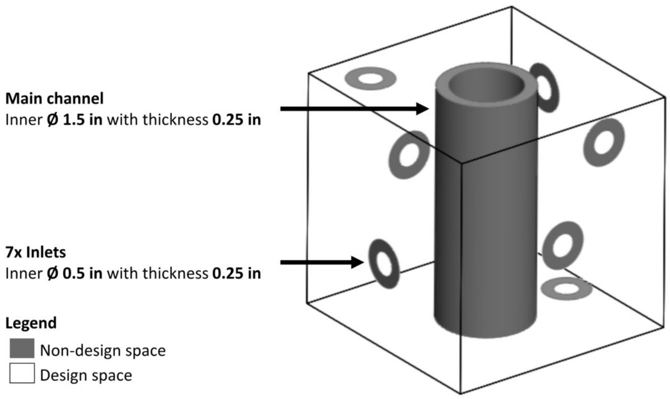


FIGURE 3: Illustrating the *design* and *non-design* space that participants were prompted to consider for the DfAM problem

To simplify and expedite the problem-solving process, a 3D model of the design and non-design space was provided to the participants. This means that participants were not required to create the design and non-design space themselves and could instead focus on designing the channels for AM. This design problem was chosen to reflect the 3D spatial complexity inherent to AM processes and the designs enabled by them. Specifically, the problem forced participants to visualize geometric features in multiple directions and assess their manufacturability for AM. Such spatial complexity also made this a suitable problem to extract the effects of immersion in AM contexts.

Participants were further instructed to consider material extrusion (ME) as the AM process for the design problem. Details about the printer were provided as follows:

- The printer prints with 100% infill (i.e., a solid part)
- It has a 2.5 mm nozzle diameter that deposits material at a 1.875 mm layer height
- The machine has a 7 x 7 x 7 cubic inch build volume

A virtual AM program was provided by the authors to slice and print their solution and determine its manufacturability within

[2]Website for three.js: https://threejs.org/
[3]Source for cura-wasm: https://github.com/cloud-cnc/cura-wasm

these parameters. Participants were required to manufacture each of their solutions using this program to determine their manufacturability before submitting one as their final design. This requirement established a *pre-reviewed* baseline and allowed the comparison to the *post-reviewed* manufacturability outcomes. Specifically, participants were to reason if the default orientation was the best orientation for manufacturing, or if another orientation was better. Changes to the outcomes could, therefore, be attributed to a designer's engagement with the design when fabricating it in their assigned modality.

The design prompt instructed participants to identify a solution that demonstrated favorable manufacturability with AM. To help with this, the AM program displayed the manufacturability score, the time to print completion, the weight of their part, and the amount of support material used for the print. This information was to be used to compare the manufacturability outcomes between the two print orientations. The manufacturability score in particular provided a general assessment of the favorability of the solution for AM. This means that the higher the manufacturability score, the more favorable the solution was for AM. To receive a high score, favorable solutions were expected to:

1. Weigh as little as possible
2. Require little to no wasted support material to fabricate
3. Build in the shortest amount of time possible.

Manufacturability score was calculated using Equation 1 where t_{max} and m_{max} were the outcomes from printing a solid cube occupying the entire design space, m_{min} was the mass of a *minimum viable design* for the problem, and t_{min} was the theoretical minimum print time. Here, m_{min} was obtained by the authors by exploring multiple likely solutions to the design problem and was used to penalize unreasonable solutions. However, t_{min} was set to a theoretical minimum to generously allow solutions not accounted for by the authors, thus rewarding creativity.

$$\text{Score} = 100 \times \left(1 - \frac{t_{norm} + m_{norm}}{2}\right) \quad (1)$$

where

$$t_{norm} = \max\left(0,\ \min\left(1, \frac{t - t_{min}}{t_{max} - t_{min}}\right)\right)$$

$$m_{norm} = \max\left(0,\ \min\left(1, \frac{m - m_{min}}{m_{max} - m_{min}}\right)\right)$$

and

$$t_{min} = 0 \text{ mins},\ t_{max} = 239 \text{ mins}$$

$$m_{min} = 300 \text{ g},\ m_{max} = 4974 \text{ g}$$

It is important to note that Equation 1 is a normalized cost function. Unlike a normal cost function which is not bounded, this manufacturability score is bounded between 0 and 100. This bounding resembles a grade-like system, serving to make the manufacturability assessment more relatable and intuitive to the participants who were students. Using such a scale for the score aimed to instill internal motivation in the participants, encouraging them to identify the more favorable solutions.

3.4 Gauging cognitive load

After manufacturing their designs and identifying the best solution, participants reported their experienced cognitive load from completing the exercise. They used the Workload Profile Assessment (WPA) tool[52] to quantify the cognitive load they experienced. Compared to the Subjective Workload Assessment Technique and the NASA Task Load Index, the WPA's higher sensitivity was preferred for such quantitative assessments[53]. Participants scored eight workload profile dimensions between 0 and 10 to represent their mental exertion. These eight dimensions spanned Perceptual, Response, Spatial, Verbal, Visual, Auditory, Manual, and Speech cognitive processing needs. Participants received a text and audio description of each dimension to review, along with an example of each dimension applied in practice.

Using these descriptions, participants assessed their cognitive load and assigned appropriate values to each dimension, one at a time. The *Verbal* and *Auditory* dimensions, though not directly applicable to the design DfAM exercise, were included to ensure consistency with the WPA tool. This is because the designed experiment did not study any tasks or elements that gave verbal instruction and audio cues. However, the WPA tool was designed to study tasks that would include such elements. The *Speech* dimension was also included under the same rationale. Additionally, this study did not check or correct for any misinterpretations of the dimensions by the participants. Therefore, the inclusion of these dimensions ensured that all the necessary information was collected to study the cognitive load experienced by the participants.

4. RESULTS

This study measured the effects of immersion on the manufacturability outcomes of an artifact designed for AM and the cognitive load experienced from the DfAM problem-solving experience. Due to the study's opt-in flexibility, participants inconsistently completed the study's elements, resulting in different sample sizes for the different analyses. A total of 40 participants (CAx = 19, VR = 21) generated 3D models for the design problem and manufactured them in either the CAx or VR modality. This sample set serves as the primary pool of relevant data for the study. From this set, 30 participants completed the pre-study questionnaire that recorded their background in AM, ME, DfME, and CAx or VR. Additionally, 25 (CAx = 10, VR = 15) out of the original 40 reported their cognitive load from the DfAM exercise after completing the design problem. Furthermore, only 14, (CAx = 8, VR = 6) submitted *finished* 3D solutions, that included channels for all the inlets connecting to the outlet as required by the design prompt. This section presents analyses of the background data, the manufacturability outcomes, and the cognitive load data with their respective sample sizes. Specifically, Section 4.1 informs on the backgrounds of 30 participants, Section 4.2 the manufacturability outcomes of 40 designs, and Section 4.3 the cognitive load experienced by 25 participants. Section 5 later distinguishes the trends observed with finished and unfinished designs further informing on the underlying phenomenon in the main findings in Section 4.2.

To statistically explain the background, cognitive load, and evaluation time data, linear regression models (lm) were generated.

These models explained the effects of only one independent variable, i.e., Condition, on the dependent variables. Linear mixed-effects regression modeling (lmer) was used to statistically analyze the change in manufacturability score, print time, and support material usage. These models explained the effects of two independent variables, i.e., Condition and Stage, on the dependent variables, where Stage was the repeated measure. Pairwise comparisons between variables were done using Estimated Marginal Means tests. The *lmer* utilized restricted maximum likelihood estimation to iteratively modify the parameter estimates with a minimized log-likelihood function. The *lm* and *lmer* model assumptions were checked using the Peña and Slate[54] and the Loy and Hofmann[55] procedures respectively. The R programming language was used to perform all the statistical analyses and assumption checks in this research Unless otherwise specified, this research did not find any observable violations and relies on the acceptable range for the robustness of the respective regression models. A 95% confidence interval was used to determine statistical significance (i.e., $p < 0.05$). The p-values from the *lmers* are adjusted using the Kenward and Rogers adjustment to account for the small sample size. Those from the pairwise comparisons were adjusted using the Bonferroni method to account for multiple comparisons. This adjustment minimized the chance of false positives. As such, any observed significance in the findings was likely not due to random chance. All potential outliers in the data were retained in each analysis. The reported findings are presented in the following format: $b = 0.00$, $F(n,m) = 0.00$ $[t(n,m) = 0.00]$, $p = 0.00$. Here, b is the regression coefficient (i.e., slope), F is the F-statistic, t is the t-statistic, and p is the p-value. Here n and m are the degrees of freedom in the numerator and denominator respectively.

4.1 Background analysis

Analyzing the prior knowledge of AM, ME, and DfME concepts from the 30 participants helped account for the effects of such knowledge on the measured manufacturability outcomes and cognitive load. The distributions of the prior knowledge in AM, ME, and DfME were regressed on the centered condition (CAx = -0.5, VR = 0.5) for the analysis. The results showed no observable significant difference between the three conditions in their prior knowledge of AM, $b = -0.11$, $F(1,28) = 0.12$, $[t(1,28) = -0.34]$, $p = 0.737$, of ME, $b = -0.27$, $F(1,28) = 0.55$, $[t(1,28) = -0.74]$, $p = 0.465$, and of DfME, $b = -0.11$, $F(1,28) = 0.08$, $[t(1,28) = -0.29]$, $p = 0.776$. This trend is observed in Figure 4, where participants in all the conditions reported similar prior knowledge of AM, ME, and DfME. Specifically, they shared that they generally had *some informal* or *formal* knowledge of each of the topics.

Participants in the CAx and VR conditions also described their proficiency with their respective modalities. Analyzing this data established the need for a tutorial phase for each condition before the main study. The collapsed technology proficiency was regressed on the centered condition (CAx = -0.5, VR = 0.5). As expected, participants generally showed a significantly higher proficiency for CAx technology than for VR technology, $b = -1.72$, $F(1,28) = 13.68$, $[t(1,28) = -3.7]$, $p = 0.001$. Specifically, participants in the CAx condition were generally *extremely comfortable* or considered themselves *experts* with CAx

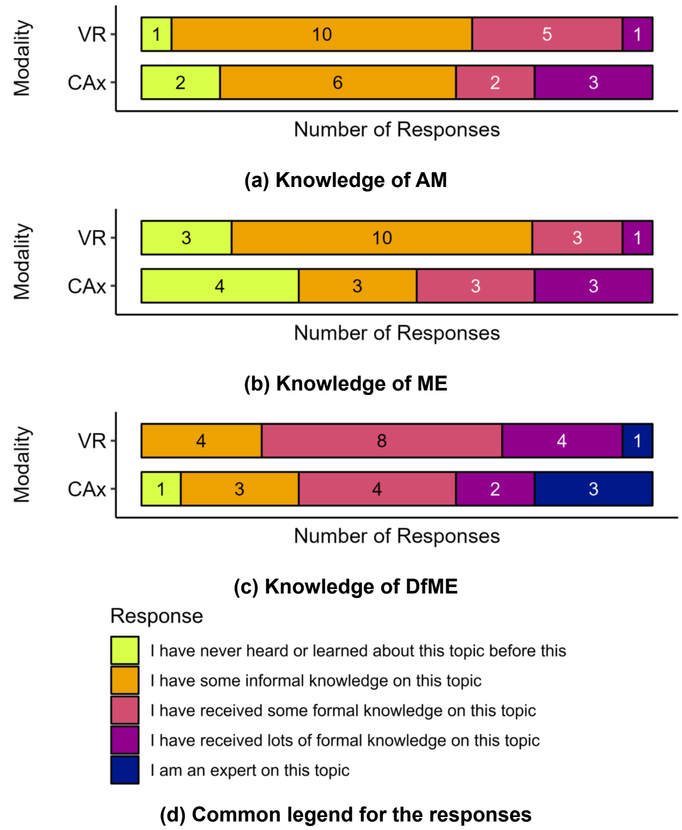


FIGURE 4: Presenting the distribution of reported prior knowledge of AM, ME, and DfME among the participants in the two conditions

technology; however, those in the VR condition had generally *never worked with* VR technology or were *slightly comfortable* with it. This trend shown in Figure 5 was expected because students had likely completed CAx/CAD course requirements but likely not any VR coursework. Though expected, the trend echoes the need for a tutorial on VR to balance the technological proficiency between modalities before an AM study[45,56].

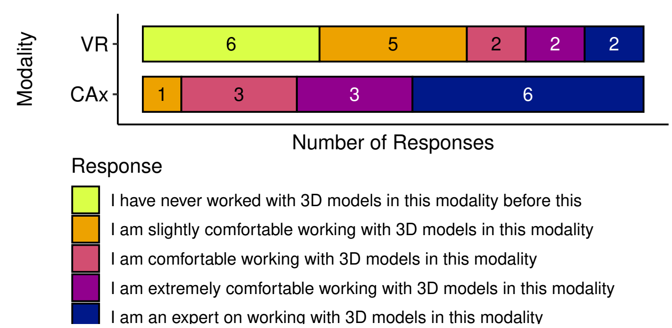


FIGURE 5: Presenting the distribution of reported proficiency on working with CAx and VR modalities

4.2 Manufacturability outcomes

The results presented in this section are observations from 40 designs submitted for the study. Analyzing this data helped address the first research question, i.e., identifying the effects of varying levels of immersion on manufacturability outcomes. For this analysis, the manufacturability score, print time, and support material usage were regressed on the centered variables for *Condition*, and *Stage* as a covariate. Evaluation time was regressed on the centered variable for *Condition* only.

Condition served as a between-subjects variable centered around the three studied conditions: CAE = -0.5, VR = 0.5. *Stage* served as a repeated measure for the within-subjects design, centered around the time points in the DfAM exercise: Pre = -0.5, Post = 0.5. The pre and post-stages represent the outcomes observed before and after participants interacted with the design respectively. Comparing the outcomes from the two stages indicates whether participants explored new print orientations for their design besides the one they started with. This comparison sheds light on the influence the CAx and VR modalities had on a participant's engagement to identify a better print orientation for their design. The presented results from the regression analysis focus on each detailed effect when controlling for all other main effects in the model. Only the interaction effects between *Condition* and *Stage* were considered in the analysis. These effects indicate the significance of the *change* in the manufacturability outcomes between the pre and post-stages.

The main analysis showed no significant effect of *Condition* on *Evaluation Time*, *b = -0.91, F(1,38) = 0.65, [t(1,38) = -0.8], p = 0.426*. Figure 6 shows that participants generally spent similar time in the CAx and VR conditions to evaluate their designs.

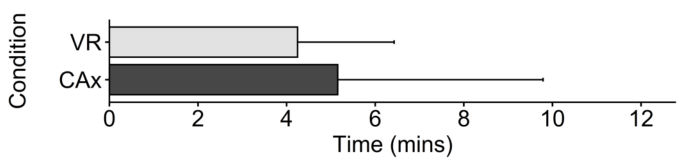


FIGURE 6: Showing the distribution of time spent evaluating one design at a time between the two conditions

The main analysis showed no significant effect of *Condition* on the *Score*, *Print Time*, and *Support Usage* (see Table 1). As seen in Figure 7, participants generally yielded similar manufacturability scores, print completion times, and support material usage for the designs between the modalities. This means that the manufacturability outcomes were not significantly different in the CAx and VR conditions. However, the analysis did show a significant effect of *Stage* on *Score* and *Print Time* with an emerging trend in *Support Usage*. As also seen in Figure 7, participants generally yielded higher manufacturability scores, shorter print completion times, and lower support material usage for their designs at the *Post* stage than at the *Pre* stage. This means that participants generally identified a better print orientation for their design after interacting with it in their assigned modalities.

Estimating a two-way interaction between *Condition* and *Stage* explained how the change in the outcomes differed between the modalities, i.e., the difference in *Score*, *Print Time*, and *Support Usage* between the pre and post-stages. The analysis showed no significant effect from the interaction between *Condition* and *Stage* on *Score*, *Print Time*, and *Support Usage* (see Table 1). This means that participants generally made similar changes to the manufacturability outcomes between the modalities.

The pairwise comparison of the two stages between each condition further suggested that the *Pre* and *Post* values for each outcome were similar between CAx and VR. However, participants in the VR condition yielded a higher change in *Score* and *Print Time* than those in the CAx condition (see Figures 7a and 7b). An emerging trend can also be observed in *Support Usage* (see Figure 7c). This means that *Condition* may not significantly affect the manufacturability outcomes, but it may strongly influence the *change* in these outcomes.

TABLE 1: Listing the general effects of each variable on the manufacturability outcomes of all the designs

(a) Manufacturability score

Variable	Estimate	F(1, 38)	t.ratio	p.value
Condition	1.37	0.09	0.29	0.770
Stage	3.69	6.67	2.58	0.014
Condition:Stage	4.33	2.29	1.51	0.138

(b) Time to print completion

Variable	Estimate	F(1, 38)	t.ratio	p.value
Condition	-0.22	0.44	-0.67	0.509
Stage	-0.29	5.18	-2.28	0.029
Condition:Stage	-0.24	0.91	-0.95	0.347

(c) Support material used

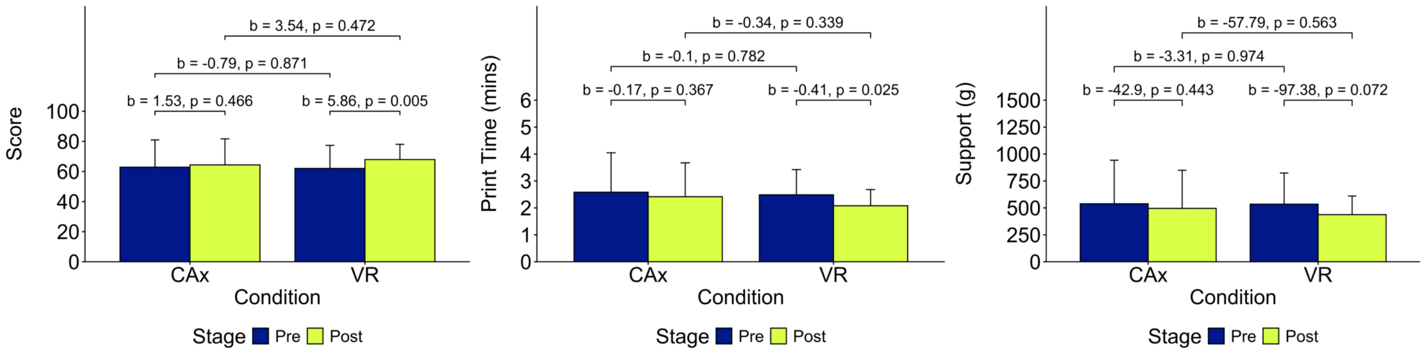
Variable	Estimate	F(1, 38)	t.ratio	p.value
Condition	-30.55	0.11	-0.33	0.740
Stage	-70.14	3.37	-1.84	0.074
Condition:Stage	-54.49	0.51	-0.71	0.480

4.3 Cognitive load

Results presented in this section are observations from data provided by 25 participants. Analyzing the data collected from this group helped address the second research question, i.e., identifying the effects of varying levels of immersion on cognitive load. For this analysis, the *Verbal*, *Auditory*, and *Speech* dimensions were excluded (though included in the survey, see Section 3.4) and the *remaining* five dimensions were regressed on the centered variable for *Condition*. *Condition* served as a between-subjects variable centered around the three studied conditions: CAx = -0.5, VR = 0.5. The main analysis showed no statistically significant difference in cognitive load for any of the dimensions between the conditions (see Table 2 and Figure 8). This suggests that determining the manufacturability of one's design in CAx and VR demands similar effort across the different dimensions.

5. DISCUSSION

The goal of this study was to observe how varying levels of immersion affect the manufacturability outcomes of an artifact designed to solve a problem with AM. Specifically, participants were tasked with generating a 3D model to solve a design prompt and then manufacturing it with AM in either a CAx or VR environment. To explain the results from Section 4 from this study,



(a) Manufacturability score **(b) Time to print completion** **(c) Support material used**

FIGURE 7: Showing changes to the manufacturability outcomes as affected by the two conditions

TABLE 2: Listing the different cognitive load dimensions and showing how they differed between the conditions

Dimension	Estimate	F(1, 23)	t.ratio	p.value
Perceptual	-0.20	0.06	-0.25	0.801
Response	0.10	0.02	0.14	0.893
Spatial	-0.53	0.43	-0.65	0.520
Visual	0.23	0.10	0.31	0.759
Manual	-0.33	0.16	-0.40	0.695

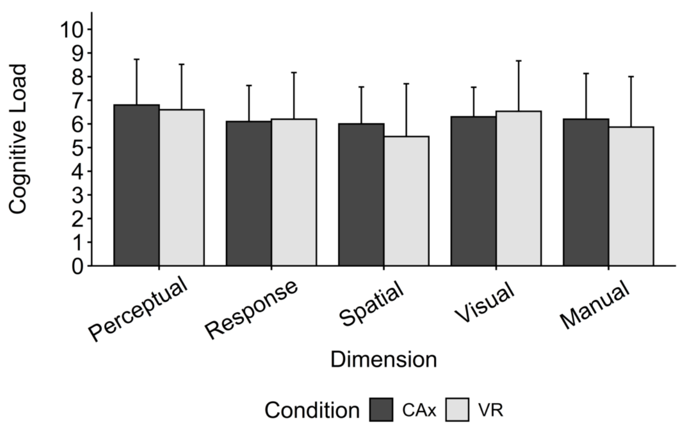


FIGURE 8: Showing the distribution of reported cognitive load as affected by the two conditions

this section first summarizes the main findings and emphasizes their broader implications. It then discusses emerging trends from a post hoc analysis to discern the underlying phenomenon.

5.1 Main findings

This study investigated two research questions to understand the effects of immersion on the manufacturability outcomes and cognitive load experienced from solving a DfAM problem.

How do differences in immersion between CAx and VR affect the change in manufacturability outcomes of a solution designed for AM?

The goal of RQ 1 was to identify the effects of varying levels of immersion on the determined manufacturability outcomes of an artifact designed for AM. The results from Section 4.2 showed that the manufacturability outcomes were not significantly different between the CAx and VR conditions. However, the results also showed that participants generally identified a better print orientation for their design after interacting with it in their assigned modalities. This is interesting because it suggests that participants reconsidered their DfAM intuition after visualizing the manufacturability of their designs in new ways. Additionally, the modalities generally did not influence the manufacturability outcomes themselves, but they did influence the change in these outcomes. Specifically, participants in the VR condition yielded a higher change in manufacturability score, print completion time, and support material usage than those in the CAx condition. Because the pre and post-values were similar between the conditions, these trends were likely due to a large difference between the pre and post-means. In other words, the statistical significance was likely due to a high nominal difference between the means and low variation within each condition.

How do the differences in immersion between CAx and VR affect the cognitive load experienced from manufacturing of a solution designed for AM?

The goal of RQ 2 was to identify the effects of varying levels of immersion on the cognitive load experienced from solving a DfAM problem. The results from Section 4.3 showed that the cognitive load experienced by participants was not significantly different between the CAx and VR conditions. This means that working in CAx and VR demanded similar mental effort across the different dimensions while determining the manufacturability of one's design. These findings resemble the effects observed on cognitive load from previous investigations of using VR in AM and DfAM contexts[45,56]. Specifically, the results suggest that the added immersion in VR may not significantly change the mental effort required to work with AM and DfAM applications.

5.2 Post hoc trends

This study used a design challenge to encourage 3D design thinking that required skill in 3D spatial perception and visualization, a shared characteristic of DfAM and VR. However, the likely lack of motivation or fundamental CAD skills in the participants limited the study's dataset to 14 finished designs.

The effects of immersion observed on the manufacturability outcomes of the finished designs must be isolated from those for the unfinished designs. This is because participants who submitted unfinished designs did not apply DfAM considerations for the required functionality specified in the design prompt. In other words, they did not explore connections from all the inlets to the outlet, limiting the challenge to their 3D spatial perception and visualization ability. The degree to which the design was unfinished was irrelevant to this classification. Independent post hoc analyses of the finished and unfinished designs, therefore, discerned the underlying phenomenon in the main findings.

First, analyzing data from only the 14 *finished* designs showed a significant effect of the interaction between *Condition* and *Stage* on *Score* (see Table 3). No observable significance was found for the interaction between *Condition* and *Stage* on *Print Time* and *Support Usage*. This means that participants who reviewed finished designs generally yielded a significantly higher change in manufacturability score with the increase in immersion between the modalities. The pairwise comparison of the pre and post-stages shown in Figure 9a explained that participants in VR yielded a higher change in *Score* than those in CAx. Figures 9b and 9c indicate that this general trend was attributed to a significant reduction in *Print Time* and *Support Usage* in VR. Participants in CAx, however, also showed emerging trends for a high change in *Score*, seemingly attributed to a reduction in *Support Usage*. These trends are observed with similar pre and post-values for the manufacturability outcomes between the modalities.

TABLE 3: Listing the general effects of each variable on the manufacturability outcomes of the finished designs

(a) Manufacturability score

Variable	Estimate	F(1, 12)	t.ratio	p.value
Condition	-2.06	0.09	-0.31	0.765
Stage	11.40	25.36	5.04	0.000
Condition:Stage	11.54	6.50	2.55	0.025

(b) Time to print completion

Variable	Estimate	F(1, 12)	t.ratio	p.value
Condition	-0.15	0.07	-0.27	0.794
Stage	-0.86	10.46	-3.23	0.007
Condition:Stage	-0.54	1.04	-1.02	0.327

(c) Support material used

Variable	Estimate	F(1, 12)	t.ratio	p.value
Condition	-4.83	0.00	-0.03	0.975
Stage	-264.38	14.09	-3.75	0.003
Condition:Stage	-191.25	1.84	-1.36	0.199

Next, analyzing data from only the 26 *unfinished* designs showed no observable significance for the interaction between *Condition* and *Stage* on *Score*, *Print Time*, and *Support Usage* (see Table 4). This means that participants who reviewed unfinished designs generally yielded similar changes in manufacturability score with the increase in immersion between the modalities. The pairwise comparisons of the different outcomes suggest that participants yielded nearly identical values for *Score*, *Print Time*, and *Support Usage* between the modalities and the stages (see Figure 10). Lastly, participants showed no observable difference in the time they spent manufacturing the *finished* designs, $b = -2.42$, $F(1,12) = 1.1$, $[t(1,12) = -1.05]$, $p = 0.315$ (see Figure 11a). This was also the case for the *unfinished* designs as shown in Figure 11b, $b = 0.02$, $F(1,24) = 0$, $[t(1,24) = 0.01]$, $p = 0.989$.

TABLE 4: Listing the general effects of each variable on the manufacturability outcomes of the unfinished designs

(a) Manufacturability score

Variable	Estimate	F(1, 24)	t.ratio	p.value
Condition	-1.28	0.11	-0.34	0.740
Stage	-0.06	0.00	-0.05	0.962
Condition:Stage	2.79	1.25	1.12	0.275

(b) Time to print completion

Variable	Estimate	F(1, 24)	t.ratio	p.value
Condition	0.04	0.03	0.17	0.864
Stage	0.01	0.02	0.13	0.894
Condition:Stage	-0.26	1.84	-1.36	0.187

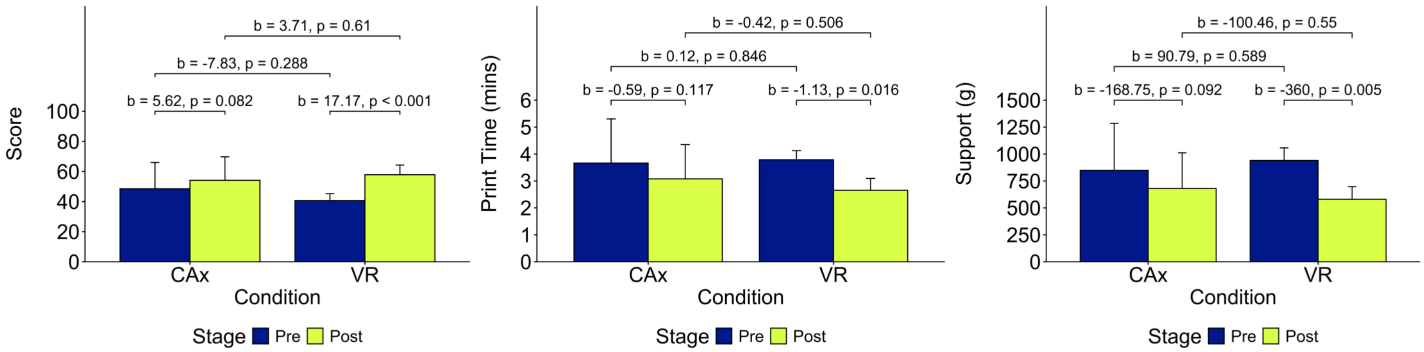
(c) Support material used

Variable	Estimate	F(1, 24)	t.ratio	p.value
Condition	40.41	0.32	0.56	0.579
Stage	28.15	0.81	0.90	0.378
Condition:Stage	-40.97	0.43	-0.65	0.520

Participants who submitted unfinished designs did not meet the prompted design requirements. As a result, the mixture of finished and unfinished designs in the main analysis obscured the insight extracted from the main findings. Conducting a post hoc analysis of the finished and unfinished designs isolated the effects observed specific to each. The results of these analyses showed that only the outcomes measured for the finished design represented the intended phenomenon that was measured by this research, yielding more reliable inferences. An interesting inference from this was that participants in the VR condition yielded a significantly higher change in the manufacturability outcomes of their designs than those in the CAx condition. Although this was hypothesized, it is important to note that the sample size for the finished designs was 14 (CAx = 8, VR = 6), which is a small sample size. Further investigation with a larger sample is required to strengthen potential statistical significance.

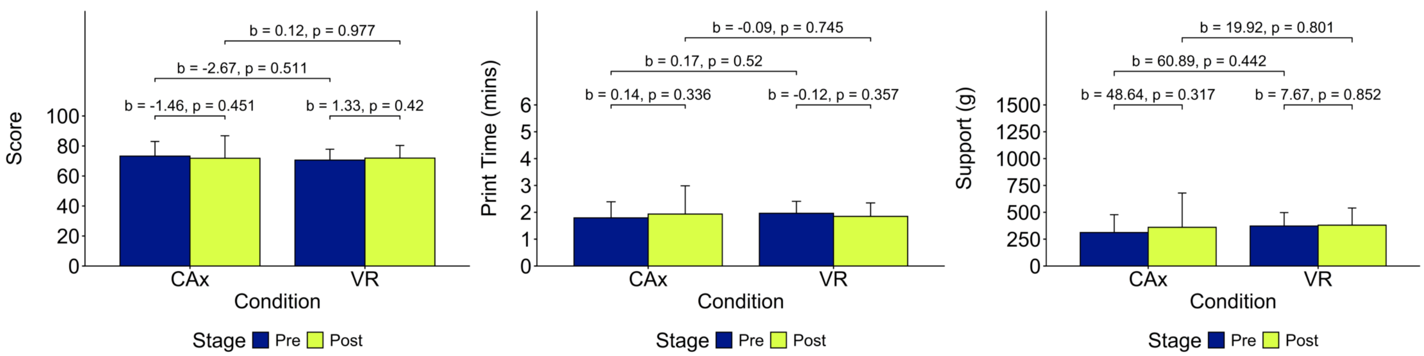
6. CONCLUSION

This research studied the use of VR experiences for DfAM problem-solving. Designers generated original designs for a design problem and additively manufactured them in either a CAx or VR modality to evaluate their design's manufacturability. The goal was to understand how differences in immersion between modalities affect 1. the manufacturability score of the design, 2. the time taken for print completion, 3. the support material used for the print, and 4. the time spent identifying the best solution.



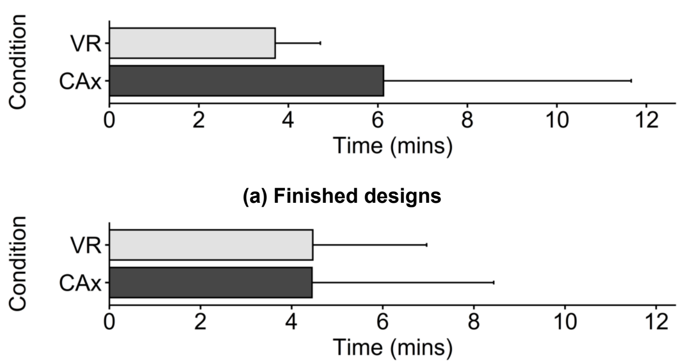
(a) Manufacturability score **(b) Time to print completion** **(c) Support material used**

FIGURE 9: Showing changes to the manufacturability outcomes of the finished designs as affected by the two conditions



(a) Manufacturability score **(b) Time to print completion** **(c) Support material used**

FIGURE 10: Showing changes to the manufacturability outcomes of the unfinished designs as affected by the two conditions



(a) Finished designs

(b) Unfinished designs

FIGURE 11: Showing the distribution of time spent evaluating the finished and unfinished designs between the two conditions

Participants evaluated their designs for manufacturability by ME and identified the best print orientation for their designs. Results suggest that experiential outcomes were not significantly different between the CAx and VR conditions. However, the results also showed that participants generally identified a better print orientation for their design after interacting with it in their assigned modalities. Additionally, the modalities generally did not influence the manufacturability outcomes themselves, but they did influence the change in these outcomes. Specifically, participants in the VR condition showed trends in yielding a higher change in manufacturability score, print completion time, and support material usage than those in the CAx condition.

A closer inspection of the observations indicated that the effects observed on the manufacturability outcomes were driven by the effects of immersion on the *finished* designs. This is because the manufacturability outcomes were identical between the conditions and the stages for the unfinished designs. This implies that participants in VR yielded significantly different outcomes to problem-solving with AM when working with fundamentally complex designs. These contributions have significant implications for how future designers are trained in DfAM problem-solving to meet the AM demands in the workforce. Specifically, immersive mediums show the potential to yield a higher change in the manufacturability outcomes of designs for AM. The modality of DfAM problem-solving thus impacts the quality of the end-use parts and the time and material requirements from the fabrication process.

While these are interesting implications, these findings must be considered with certain limitations of this work. This research limited its scope toward manufacturability evaluation for ME. Material extrusion is a relatively more accessible and functionally less complex process than processes like powder bed fusion. Therefore, the findings from this research may not be generalizable to other AM processes. Future work must expand on these findings and explore learning and intuition development for multiple AM processes. Doing so will aid industries in improving their digital design processes by empowering their designers with insight into the range of AM solutions. This research also studied designers with beginner and intermediate CAD skills. Future work must account for CAD expertise and study the effects of immersion in problem-solving with AM on designers with varying levels of CAD skills. Additionally, the study did not investigate how problem-solving in immersive versus non-immersive environments changes the design process. Specifically, studying how working in VR and CAx affects changes to the designs generated to solve a design challenge. Future work must observe the iterative design process and document how designers' application of DfAM principles changes with immersion over multiple iterations.

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REFERENCES

[1] Jiang, Ruth, Kleer, Robin, and Piller, Frank T. "Predicting the Future of Additive Manufacturing: A Delphi Study on Economic and Societal Implications of 3D Printing for 2030," *Technological Forecasting and Social Change*, Vol. 117 (2017): pp. 84–97. DOI 10.1016/j.techfore.2017.01.006.

[2] Simpson, Timothy W., Williams, Christopher B., and Hripko, Michael. "Preparing Industry for Additive Manufacturing and Its Applications: Summary & Recommendations from a National Science Foundation Workshop," *Additive Manufacturing*, Vol. 13 (2017): pp. 166–178. DOI 10.1016/j.addma.2016.08.002.

[3] Meisel, Nicholas, and Williams, Christopher. "An Investigation of Key Design for Additive Manufacturing Constraints in Multimaterial Three-Dimensional Printing," *Journal of Mechanical Design*, Vol. 137 No. 11 (2015): p. 111406. DOI 10.1115/1.4030991.

[4] Thompson, Mary Kathryn, Moroni, Giovanni, Vaneker, Tom, Fadel, Georges, Campbell, R. Ian, Gibson, Ian, Bernard, Alain, Schulz, Joachim, Graf, Patricia, Ahuja, Bhrigu, and Martina, Filomeno. "Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints," *CIRP Annals*, Vol. 65 No. 2 (2016): pp. 737–760. DOI 10.1016/j.cirp.2016.05.004.

[5] Ford, Simon, and Despeisse, Mélanie. "Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges," *Journal of Cleaner Production*, Vol. 137 (2016): pp. 1573–1587. DOI 10.1016/j.jclepro.2016.04.150.

[6] Ford, Simon, and Minshall, Tim. "Invited Review Article: Where and How 3D Printing Is Used in Teaching and Education," *Additive Manufacturing*, Vol. 25 (2019): pp. 131–150. DOI 10.1016/j.addma.2018.10.028.

[7] Alfaify, Abdullah, Saleh, Mustafa, Abdullah, Fawaz M., and Al-Ahmari, Abdulrahman M. "Design for Additive Manufacturing: A Systematic Review," *Sustainability*, Vol. 12 No. 19 (2020): p. 7936. DOI 10.3390/su12197936.

[8] Pei, Eujin, Monzón, Mario, and Bernard, Alain, eds. *Additive Manufacturing – Developments in Training and Education*, Springer International Publishing, Cham (2019). DOI 10.1007/978-3-319-76084-1.

[9] Huang, Yong, and Leu, Ming C. "Frontiers of Additive Manufacturing Research and Education," (2014):

[10] Thomas-Seale, L.E.J., Kirkman-Brown, J.C., Attallah, M.M., Espino, D.M., and Shepherd, D.E.T. "The Barriers to the Progression of Additive Manufacture: Perspectives from UK Industry," *International Journal of Production Economics*, Vol. 198 (2018): pp. 104–118. DOI 10.1016/j.ijpe.2018.02.003.

[11] Lauff, Carlye A., Kotys-Schwartz, Daria, and Rentschler, Mark E. "What Is a Prototype? What Are the Roles of Prototypes in Companies?" *Journal of Mechanical Design*, Vol. 140 No. 6 (2018): DOI 10.1115/1.4039340.

[12] Camburn, Bradley, Dunlap, Brock, Gurjar, Tanmay, Hamon, Christopher, Green, Matthew, Jensen, Daniel, Crawford, Richard, Otto, Kevin, and Wood, Kristin. "A Systematic Method for Design Prototyping," *Journal of Mechanical Design*, Vol. 137 No. 8 (2015): p. 081102. DOI 10.1115/1.4030331.

[13] Grodotzki, Joshua, Ortelt, Tobias R., and Tekkaya, A. Erman. "Remote and Virtual Labs for Engineering Education 4.0: Achievements of the ELLI Project at the TU Dortmund University," *Procedia Manufacturing*, Vol. 26 (2018): pp. 1349–1360. DOI 10.1016/j.promfg.2018.07.126.

[14] Hernandez-de-Menendez, Marcela, Escobar Díaz, Carlos A., and Morales-Menendez, Ruben. "Engineering Education for Smart 4.0 Technology: A Review," *Int J Interact Des Manuf*, Vol. 14 No. 3 (2020): pp. 789–803. DOI 10.1007/s12008-020-00672-x.

[15] Henri, Maria, Johnson, Michael D., and Nepal, Bimal. "A Review of Competency-Based Learning: Tools, Assessments, and Recommendations," *Journal of Engineering Education*, Vol. 106 No. 4 (2017): pp. 607–638. DOI 10.1002/jee.20180.

[16] Yang, Sheng, Page, Thomas, and Zhao, Yaoyao Fiona. "Understanding the Role of Additive Manufacturing Knowledge in Stimulating Design Innovation for Novice Designers," *Journal of Mechanical Design*, Vol. 141 No. 2 (2018): DOI 10.1115/1.4041928.

[17] Ponche, Remi, Kerbrat, Olivier, Mognol, Pascal, and Hascoet, Jean-Yves. "A Novel Methodology of Design for Additive Manufacturing Applied to Additive Laser Manufacturing Process," *Robotics and Computer-Integrated Manufacturing*, Vol. 30 No. 4 (2014): pp. 389–398. DOI 10.1016/j.rcim.2013.12.001.

[18] Kumke, Martin, Watschke, Hagen, Hartogh, Peter, Bavendiek, Ann-Kathrin, and Vietor, Thomas. "Methods and Tools for Identifying and Leveraging Additive Manufacturing Design Potentials," *Int J Interact Des Manuf*, Vol. 12 No. 2 (2018): pp. 481–493. DOI 10.1007/s12008-017-0399-7.

[19] Huang, Yong, Leu, Ming C., Mazumder, Jyoti, and Donmez, Alkan. "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations," *Journal of Manufacturing Science and Engineering*, Vol. 137 No. 1 (2015): p. 014001. DOI 10.1115/1.4028725.

[20] Rayna, Thierry, and Striukova, Ludmila. "From Rapid Prototyping to Home Fabrication: How 3D Printing Is Changing Business Model Innovation," *Technological Forecasting and Social Change*, Vol. 102 (2016): pp. 214–224. DOI 10.1016/j.techfore.2015.07.023.

[21] Buehler, Erin, Easley, William, McDonald, Samantha, Comrie, Niara, and Hurst, Amy. "Inclusion and Education: 3D Printing for Integrated Classrooms," *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility*, pp. 281–290, New York, NY, USA, October 26, 2015. DOI 10.1145/2700648.2809844.

[22] Kane, Shaun K., and Bigham, Jeffrey P. "Tracking @Stemxcomet: Teaching Programming to Blind Students via 3D Printing, Crisis Management, and Twitter," *Proceedings of the 45th ACM Technical Symposium on Computer Science Education*, pp. 247–252, New York, NY, USA, March 5, 2014. DOI 10.1145/2538862.2538975.

[23] Mourtzis, Dimitris. "Simulation in the Design and Operation of Manufacturing Systems: State of the Art and New Trends," *International Journal of Production Research*, Vol. 58 No. 7 (2020): pp. 1927–1949. DOI 10.1080/00207543.2019.1636321.

[24] Soori, Mohsen, Arezoo, Behrooz, and Dastres, Roza. "Virtual Manufacturing in Industry 4.0: A Review," *Data Science and Management*, Vol. 7 No. 1 (2024): pp. 47–63. DOI 10.1016/j.dsm.2023.10.006.

[25] Abdul Kadir, Aini, Xu, Xun, and Hämmerle, Enrico. "Virtual Machine Tools and Virtual Machining—A Technological Review," *Robotics and Computer-Integrated Manufacturing*, Vol. 27 No. 3 (2011): pp. 494–508. DOI 10.1016/j.rcim.2010.10.003.

[26] Lynn, Roby, Saldana, Christopher, Kurfess, Thomas, Reddy, Nithin, Simpson, Timothy, Jablokow, Kathryn, Tucker, Tommy, Tedia, Saish, and Williams, Christopher. "Toward Rapid Manufacturability Analysis Tools for Engineering Design Education," *Procedia Manufacturing*, Vol. 5 (2016): pp. 1183–1196. DOI 10.1016/j.promfg.2016.08.093.

[27] Deshpande, Amit A., and Huang, Samuel H. "Simulation Games in Engineering Education: A State-of-the-Art Review," *Comput. Appl. Eng. Educ.*, Vol. 19 No. 3 (2011): pp. 399–410. DOI 10.1002/cae.20323.

[28] de Jong, Ton, Linn, Marcia C., and Zacharia, Zacharias C. "Physical and Virtual Laboratories in Science and Engineering Education," *Science*, Vol. 340 No. 6130 (2013): pp. 305–308. DOI 10.1126/science.1230579.

[29] Ouyang, Shu-Guang, Wang, Gang, Yao, Jun-Yan, Zhu, Guang-Heng-Wei, Liu, Zhao-Yue, and Feng, Chi. "A Unity3D-Based Interactive Three-Dimensional Virtual Practice Platform for Chemical Engineering," *Comput Appl Eng Educ*, Vol. 26 No. 1 (2018): pp. 91–100. DOI 10.1002/cae.21863.

[30] Renner, Alex, Holub, Joseph, Sridhar, Shubang, Evans, Gabe, and Winer, Eliot. "A Virtual Reality Application for Additive Manufacturing Process Training," Proceedings of the *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, *Volume 1A: 35th Computers and Information in Engineering Conference*, p. V01AT02A033, Boston, Massachusetts, USA, August 2, 2015. DOI 10.1115/detc2015-47807.

[31] Ostrander, John K., Tucker, Conrad S., Simpson, Timothy W., and Meisel, Nicholas A. "Evaluating the Use of Virtual Reality to Teach Introductory Concepts of Additive Manufacturing," *Journal of Mechanical Design*, Vol. 142 No. 5 (2020): p. 051702. DOI 10.1115/1.4044006.

[32] Tseng, Tzu-Liang, Pan, Rong, Zheng, Jun, Awalt, Carolyn, Gonzalez, Maria, and Medina, Francisco. "Digital Additive Manufacturing for Engineering Education: A Virtual Rapid Prototyping Simulator Approach," Proceedings of the *2011 ASEE Annual Conference & Exposition*, *2011 ASEE Annual Conference & Exposition Proceedings*, pp. 22.501.1–22.501.15, Vancouver, BC, June 2011. DOI 10.18260/1-2--17782.

[33] Rutten, Nico, van Joolingen, Wouter R., and van der Veen, Jan T. "The Learning Effects of Computer Simulations in Science Education," *Computers & Education*, Vol. 58 No. 1 (2012): pp. 136–153. DOI 10.1016/j.compedu.2011.07.017.

[34] Xie, Charles, Schimpf, Corey, Chao, Jie, Nourian, Saeid, and Massicotte, Joyce. "Learning and Teaching Engineering Design Through Modeling and Simulation on a CAD Platform," *Computer Applications in Engineering Education*, Vol. 26 No. 4 (2018): pp. 824–840. DOI 10.1002/cae.21920.

[35] Halabi, Osama. "Immersive Virtual Reality to Enforce Teaching in Engineering Education," *Multimed Tools Appl*, Vol. 79 No. 3 (2020): pp. 2987–3004. DOI 10.1007/s11042-019-08214-8.

[36] Aslan, Seda Akti, and Duruhan, Kemal. "The Effect of Virtual Learning Environments Designed According to Problem-Based Learning Approach to Students' Success, Problem-Solving Skills, and Motivations," *Educ Inf Technol*, Vol. 26 No. 2 (2021): pp. 2253–2283. DOI 10.1007/s10639-020-10354-6.

[37] Soliman, Maged, Pesyridis, Apostolos, Dalaymani-Zad, Damon, Gronfula, Mohammed, and Kourmpetis, Miltiadis. "The Application of Virtual Reality in Engineering Education," *Applied Sciences*, Vol. 11 No. 6 (2021): p. 2879. DOI 10.3390/app11062879.

[38] Chen, Jyun-Chen, Huang, Yun, Lin, Kuen-Yi, Chang, Yu-Shan, Lin, Hung-Chang, Lin, Chien-Yu, and Hsiao, Hsien-Sheng. "Developing a Hands-on Activity Using Virtual Reality to Help Students Learn by Doing," *Journal of Computer Assisted Learning*, Vol. 36 No. 1 (2020): pp. 46–60. DOI 10.1111/jcal.12389.

[39] Paes, Daniel, Irizarry, Javier, and Pujoni, Diego. "An Evidence of Cognitive Benefits from Immersive Design Review: Comparing Three-Dimensional Perception and Presence Between Immersive and Non-Immersive Virtual Environments," *Automation in Construction*, Vol. 130 (2021): p. 103849. DOI 10.1016/j.autcon.2021.103849.

[40] Alhalabi, Wadee. "Virtual Reality Systems Enhance Students' Achievements in Engineering Education," *Behaviour & Information Technology*, Vol. 35 No. 11 (2016): pp. 919–925. DOI 10.1080/0144929x.2016.1212931.

[41] Wolfartsberger, Josef. "Analyzing the Potential of Virtual Reality for Engineering Design Review," *Automation in Construction*, Vol. 104 (2019): pp. 27–37. DOI 10.1016/j.autcon.2019.03.018.

[42] Guo, Ziyue, Zhou, Dong, Chen, Jiayu, Geng, Jie, Lv, Chuan, and Zeng, Shengkui. "Using Virtual Reality to Support the Product's Maintainability Design: Immersive Maintainability Verification and Evaluation System," *Computers in Industry*, Vol. 101 (2018): pp. 41–50. DOI 10.1016/j.compind.2018.06.007.

[43] Abidi, Mustufa Haider, Al-Ahmari, Abdulrahman, Ahmad, Ali, Ameen, Wadea, and Alkhalefah, Hisham. "Assessment of Virtual Reality-Based Manufacturing Assembly Training System," *Int J Adv Manuf Technol*, Vol. 105 No. 9 (2019): pp. 3743–3759. DOI 10.1007/s00170-019-03801-3.

[44] Bharathi, Ajay Karthic B. Gopinath, and Tucker, Conrad S. "Investigating the Impact of Interactive Immersive Virtual Reality Environments in Enhancing Task Performance in Online Engineering Design Activities," Proceedings of the *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, *Volume 3: 17th International Conference on Advanced Vehicle Technologies; 12th International Conference on Design Education; 8th Frontiers in Biomedical Devices*, p. V003T04A004, Boston, Massachusetts, USA, August 2, 2015. DOI 10.1115/detc2015-47388.

[45] Mathur, Jayant, Miller, Scarlett R., Simpson, Timothy W., and Meisel, Nicholas A. "Effects of Immersion on Knowledge Gain and Cognitive Load in Additive Manufacturing Process Education," *3D Printing and Additive Manufacturing*, Vol. Ahead of Print (2023): DOI 10.1089/3dp.2022.0180.

[46] Horvat, Nikola, Škec, Stanko, Martinec, Tomislav, Lukačević, Fanika, and Perišić, Marija Majda. "Comparing Virtual Reality and Desktop Interface for Reviewing 3D CAD Models," *Proc. Int. Conf. Eng. Des.*, Vol. 1 No. 1 (2019): pp. 1923–1932. DOI 10.1017/dsi.2019.198.

[47] Feeman, Seth M., Wright, Landon B., and Salmon, John L. "Exploration and Evaluation of CAD Modeling in Virtual Reality," *Computer-Aided Design and Applications*, Vol. 15 No. 6 (2018): pp. 892–904. DOI 10.1080/16864360.2018.1462570.

[48] Starkey, Elizabeth M., McKay, Alexander S., Hunter, Samuel T., and Miller, Scarlett R. "Piecing Together Product Dissection: How Dissection Conditions Impact Student Conceptual Understanding and Cognitive Load," *Journal of Mechanical Design*, Vol. 140 No. 5 (2018): p. 052001. DOI 10.1115/1.4039384.

[49] Armougum, A., Orriols, E., Gaston-Bellegarde, A., Marle, C. Joie-La, and Piolino, P. "Virtual Reality: A New Method to Investigate Cognitive Load During Navigation," *Journal of Environmental Psychology*, Vol. 65 (2019): p. 101338. DOI 10.1016/j.jenvp.2019.101338.

[50] Pontonnier, Charles, Dumont, Georges, Samani, Asfhin, Madeleine, Pascal, and Badawi, Marwan. "Designing and Evaluating a Workstation in Real and Virtual Environment: Toward Virtual Reality Based Ergonomic Design Sessions," *J Multimodal User Interfaces*, Vol. 8 No. 2 (2014): pp. 199–208. DOI 10.1007/s12193-013-0138-8.

[51] Frederiksen, Joakim Grant, Sørensen, Stine Maya Dreier, Konge, Lars, Svendsen, Morten Bo Søndergaard, Nobel-Jørgensen, Morten, Bjerrum, Flemming, and Andersen, Steven Arild Wuyts. "Cognitive Load and Performance in Immersive Virtual Reality Versus Conventional Virtual Reality Simulation Training of Laparoscopic Surgery: A Randomized Trial," *Surg Endosc*, Vol. 34 No. 3 (2020): pp. 1244–1252. DOI 10.1007/s00464-019-06887-8.

[52] Tsang, Pamela S., and Velazquez, Velma L. "Diagnosticity and Multidimensional Subjective Workload Ratings," *Ergonomics*, Vol. 39 No. 3 (1996): pp. 358–381. DOI 10.1080/00140139608964470.

[53] Rubio, Susana, Diaz, Eva, Martin, Jesus, and Puente, Jose M. "Evaluation of Subjective Mental Workload: A Comparison of SWAT, NASA-TLX, and Workload Profile Methods," *Applied Psychology*, Vol. 53 No. 1 (2004): pp. 61–86. DOI 10.1111/j.1464-0597.2004.00161.x.

[54] Peña, Edsel A, and Slate, Elizabeth H. "Global Validation of Linear Model Assumptions," *Journal of the American Statistical Association*, Vol. 101 No. 473 (2006): pp. 341–354. DOI 10.1198/016214505000000637.

[55] Loy, Adam, and Hofmann, Heike. "**HLMdiag** : A Suite of Diagnostics for Hierarchical Linear Models in *R*," *J. Stat. Soft.*, Vol. 56 No. 5 (2014): DOI 10.18637/jss.v056.i05.

[56] Mathur, Jayant, Miller, Scarlett R., Simpson, Timothy W., and Meisel, Nicholas A. "A Mixed-Methods Investigation of How Digital Immersion Affects Design for Additive Manufacturing Evaluations," *Journal of Mechanical Design*, Vol. Accepted in Press.

