

Using virtual reality to orient parts for additive manufacturing and its effects on manufacturability and experiential outcomes

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Abstract

Additive manufacturing (AM) enables the fabrication of geometrically complex designs through layer-by-layer joining of material along single or multiple directions. To determine favorable design and manufacturing solutions, designers must navigate this 3D spatial complexity while ensuring the functionality and manufacturability of their designs. Evaluating the manufacturability of their solutions necessitates modalities that help naturally visualize AM processes and the designs enabled by them. Digitally non-immersive visualization can reduce this expense, but digital immersion has the potential to further improve the experience before building. This research investigates how differences in immersion between computer-aided (CAx) and virtual reality (VR) environments affect a designer's approach to solving a build-with-AM (BAM) problem and its outcomes. First, it studies how immersion affects determining favorable build orientations when considering the additive manufacturability outcomes of designs of varying complexity. Second, it studies how immersion affects the participants' experiential outcomes, including evaluation time, attempts made, and cognitive load when solving the BAM problem. Analysis reveals that as design complexity increases, visualizing and manufacturing designs in VR improves additive manufacturability outcomes by reducing build time and support material usage compared to CAx, reducing manufacturing costs by up to 4.61% (\$32) per part. Using immersive VR also helps designers determine favorable build orientations faster with fewer attempts and without increasing the cognitive load experienced. These findings present important implications for the role of immersive experiences in preparing designers to quickly produce lower-cost and sustainable manufacturing solutions with AM.

Keywords: additive manufacturing, design for additive manufacturing, virtual reality, cognitive load, immersive user experiences, 3D printing simulation

1. Introduction

Organizations adopt advanced manufacturing technologies to address engineering challenges related to sustainability, cost, and time-to-market. Additive manufacturing (AM) presents a competitive advantage to meet these needs, offering a variety of material and process options for numerous applications[1–3]. Adoption of AM, however, requires designers who are adept in design for additive manufacturing (DfAM). Such DfAM expertise is crucial to producing parts that leverage the advantages AM offers while considering its

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limitations[4,5]. This is because DfAM knowledge facilitates unique geometric and material complexities distinct from those offered by subtractive and formative manufacturing processes[6]. However, the deficit of DfAM and AM process knowledge amongst its designers limits an organization's ability to solve engineering challenges with AM[7–9]. This deficit hinders AM adoption within organizations, and overcoming it enables AM-driven innovation[10,11]. For this purpose, emerging tools must enable designers to rapidly acquire, then apply, design and process-centric knowledge of various AM processes in problem-solving contexts. Specifically, they must be adept at evaluating and improving the additive manufacturability of designs while minimizing failures, defects, and errors. Anticipating the effects of build orientation on the quality of the additively manufactured part is a critical aspect of this evaluation. Research shows that build orientation significantly impacts surface finish, thermal distortion, and support removal[12,13] as well as the mechanical properties of the part[14,15]. To account for such effects, the literature provides rules regarding build orientation to guide design and process planning[16,17]. Past work also introduces methods to compute build orientations optimized for various criteria, further emphasizing the importance of orientation selection when building with AM[18–21]. Unlike automated tools that don't consider the design's functional requirements when identifying optimal build orientations, designers must intuit favorable orientations for a part based on its intended use. This is because designers must predict how AM process characteristics yield parts that underperform when manufactured in orientations optimized for other criteria. Possessing the ability to visually discern the manufactured quality of a design in different build orientations, while considering part functionality, is vital to problem-solving with AM. To cultivate such an ability, designers must actively experience the benefits and limitations of the AM process and intuit its DfAM considerations[22–24]. Specifically, by manufacturing functional parts and visualizing AM process effects on their design[25], then using that information to improve its manufacturability by changing build orientation. This research provides designers the experience to foster such capabilities through a build-with-AM (BAM) problem, challenging them to determine favorable build orientations for different designs. An investigation into how differences in visualization affect a designer's approach to manufacturing designs for the BAM problem is presented in this research.

Visualization plays an essential role in evaluating the form, scale, aesthetics, and ergonomics of a solution in product design processes[26,27]. For BAM problems, designers must visualize complex geometries to evaluate such functional factors and additionally discern their design's *additive* manufacturing considerations. To make informed BAM decisions, designers must first engage with AM systems to produce functional parts[25] and visualize their technological benefits and limitations[22–24]. Simultaneously referencing DfAM principles to check their manufacturability intuition promotes making informed BAM decisions, increasing design quality and performance while reducing the time and cost of development[28]. Fostering the necessary *generative* and *organic* design thinking for AM problem-solving, therefore, requires experimenting with different AM processes and their DfAM considerations[29–31]. However, access to hands-on experiences with AM systems depends on their availability, which is often limited by the cost, safety, and infrastructure requirements of the processes[32,33]. Even with physical access to safe and low-cost material extrusion (ME) systems, low manufacturing speeds limit acquiring rapid real-time feedback during problem-solving[34,35]. Designers need resources to support BAM decision-making for various AM processes and their DfAM considerations without requiring access to physical AM systems. For this purpose, different worksheets[12,13] and design heuristics[36,37] are currently used to guide DfAM considerations. However, these resources don't instruct on the significance of a designer's design decisions by demonstrating AM process effects on the manufacturability of a design. Visualizing how the layer-by-layer fabrication process affects the manufacturability of a design's features is essential to internalizing AM and DfAM concepts. To that end, *virtual manufacturing* methods, such as computer simulations and digital twins, help visualize and test products and processes before their physical realization[38–40]. Combining these methods with game-based active engagement can enhance learning and decision-making in design and manufacturing experiences[41–44]. Previous efforts in virtualized AM demonstrate such promising results when visualizing additively manufactured outcomes of different designs[45–47]. Leveraging virtualized AM systems and DfAM tools for BAM problem-solving experiences, therefore, merits an investigation.

Designers have historically relied on non-immersive computer-aided technologies (CAx) to run virtual simulations and obtain feedback on their designs[48,49]. Research shows that CAx resources help cultivate

technical skills through introspection[50], foster collaborative learning[51], improve the performance of procedural actions[43], and induce high levels of engagement at low cognitive loads[44]. Though it has its limits, digitally non-immersive problem-solving with AM is a viable alternative to physical learning and decision-making. However, adding digital immersion can influence the 3D perception of artifacts and processing of visual information[52–54], promoting knowledge acquisition, effective communication, and decision-making[55–58]. As a result, digitally immersive modalities like virtual reality (VR) yield favorable problem-solving outcomes in environments that are simulated to mimic real-world conditions[59–61], or designed to inform on actions to take in real-world situations[62–64]. Added immersion also facilitates design concept generation and analysis[65,66], bolsters creativity[67], and improves the perception of dimensional fits[68,69], improving error and defect identification in 3D models[70,71]. Positive and sustained effects on enjoyment and learning outcomes[72], as well as self-efficacy[73], can be further observed from digitally immersive visualization over passive video visualization. The literature attributes these effects of immersion to improved declarative and procedural knowledge acquisition[74], cognitive and affective skills development[75], and memory recall abilities[76]. Such attributes strongly influence how designers acquire AM process knowledge, hone their DfAM intuition, and apply their expertise to solve BAM problems. Experience in VR therefore shows more promise compared to CAx experiences for problem-solving with AM. Past work demonstrates this when teaching design and process-centric AM concepts using VR[45,46,77]. Guidance established by the authors further offers a framework for designing VR experiences for AM and DfAM contexts[78]. However, no known research applies this framework to measure how the level of immersion affects a designer’s application of this knowledge and the resulting outcomes when solving problems with AM. To address this gap, this research leverages digitally immersive and non-immersive interactive environments and investigates how designers solve a BAM problem in these environments. More precisely, it studies how the additive manufacturability of a design varies when determining a favorable build orientation in CAx and VR.

Designers must be equipped with virtual experiences to visualize AM processes and their DfAM considerations, preparing them to rapidly solve engineering problems with AM. Additive manufacturing technologies inherently utilize digital data, making them well-suited for integration with virtual environments like VR. Research also supports the use of VR to develop relevant knowledge and skills in design and engineering. Providing virtualized manufacturing feedback on designs in VR may, therefore, significantly improve a designer’s problem-solving capabilities with AM. Watching how their design materializes, similar to visuals from slicing and build preparation software, will help visualize AM process effects on the manufacturability of their designs. However, the broader impacts and trade-offs of VR experiences are still being examined and should be carefully considered. Inconclusive effects due to environmental factors during VR engagement can be observed in the literature[79–83]. Environmental and pedagogical attributes of an immersive experience strongly influence meaningful outcomes from the experience[84–88]. These various findings necessitate an investigation into the use of VR particularly for problem-solving in AM and DfAM contexts. Specifically, studying its effects on spatial perception, psychomotor ability,[89], and experienced cognitive load[90,91] is necessary to understand how immersive experiences affect problem-solving with AM. To identify the role of digitally immersive and non-immersive resources for this purpose, experiences offered by VR headsets and flat-screen computers respectively, must be examined within AM problem-solving contexts. For this purpose, this research presents a BAM problem to designers in CAx and VR environments and studies the manufacturability and experiential outcomes from determining favorable build orientations for designs of varying complexity. First, Section 2 describes the methodology used to conduct the research, including details on the pre-study procedure, the development of the virtual AM environment, and the BAM problem-solving task. Next, the data analytics and the findings are presented in Section 3, following a discussion on their implications and the likely phenomenon behind them Section 4. Finally, Section 5 summarizes the collective contributions of this research and its limitations for future work. The following research questions guide the investigation discussed in these sections:

Research Question 1. *How do the differences in immersion between CAx and VR environments affect additive manufacturability outcomes when determining favorable build orientations for designs of varying complexity?*

To study the effects of immersion on manufacturability outcomes of the designs fabricated with AM, this research question examined the following:

1. the time it takes to produce the part
2. the support material required to produce the part
3. the resultant manufacturability score of the designs

The manufacturability score of a design was based on the build time and support material used for the manufactured part. This emphasized the overall manufacturability of the design, alluding to the combined contributions of the build time and support material usage in recognizing a favorable solution. Compared to the CAx problem-solving, it was hypothesized that designers in VR identify more favorable solutions with higher manufacturability scores. To clarify, higher scores were expected due to a combination of faster builds and lower material usage. Such trends were hypothesized due to expected enhancements in spatial perception and reasoning, and object manipulation within immersive modalities during task and problem-driven design experiences[68–71]. Immersive process-centric AM reasoning was expected to amplify the effects of DfAM evaluation, resulting in improved manufacturability outcomes[77,92].

Research Question 2. *How do the differences in immersion between CAx and VR environments affect experiential outcomes when determining favorable build orientations for designs of varying complexity?*

To study the effects of immersion on the experiential differences in design evaluation for AM, this research question examined the following:

1. the time spent determining a favorable solution
2. the number of attempts made to determine a favorable solution
3. the mental effort exerted from evaluating multiple designs

The mental effort exerted by the designers was measured as the cognitive load experienced from evaluating multiple designs of varying complexity for additive manufacturability. Compared to the CAx experience, it was hypothesized that the VR experience generally yields lower reported cognitive load values. However, no significant differences between the two modalities were expected for the number of attempts made and the time spent determining a favorable solution[92]; It was expected that the effort required to perform manufacturability evaluation operations for a design, and thus the cognitive load, changed due to the change in immersion. This is because evaluations within modalities that require low effort would yield lower reported cognitive load than those that require high effort[93–96]. Such variation in effort was expected to arise due to differences in immersion, the perceived complexity of the designs, and the engagement with the designs. In other words, the designer's need to visualize AM process effects and intuit DfAM considerations was expected to influence design manipulation and information processing, thus affecting the experienced cognitive load due to varying immersion levels[77,92].

2. Materials and methods

Participating in the designed study involved describing one's knowledge in AM, VR, and CAx, solving a build-with-AM problem in CAx and VR, and reporting on their overall experience working in those environments. Each step as illustrated in Figure 1 was performed on an online Qualtrics survey. This includes engaging with the questionnaires, instructions, and the CAx and VR AM environments. The remainder of this section provides further details on each step, starting with Section 2.1 explaining the pre-study procedure. Section 2.2 describes the design of the virtual AM environment and Section 2.3 the details about the BAM problem. Lastly, Section 2.4 describes the measurement of cognitive load after the BAM exercise.

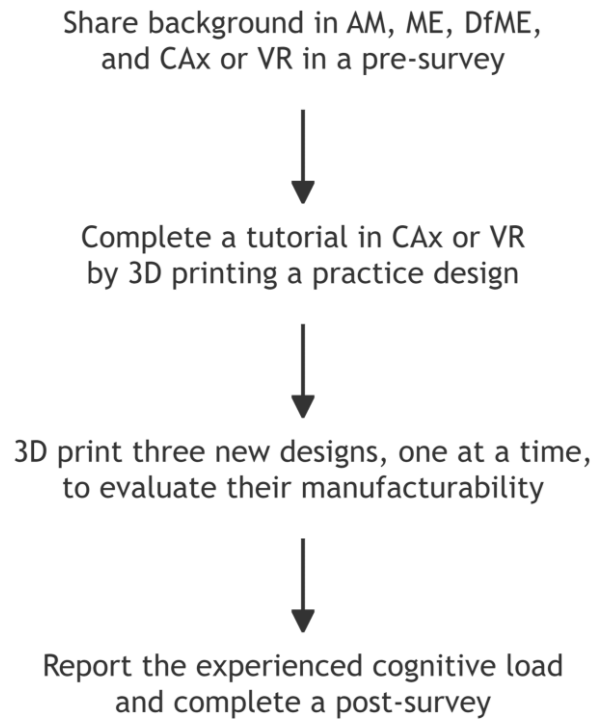


Figure 1: Illustrating the order of steps completed by the participants in the CAx and VR conditions for the designed study

2.1. Pre-study procedure

The pre-study procedure employed for this research was identical to that used in past work[77,92]. Second and third-year undergraduate students from an engineering design methodology course at an R1 university participated in this research. The students were first informed of their rights and options as participants as per Internal Review Board (IRB) protocol. This included the right to opt out of the study at any time without penalty as well as the right to request their data be removed from the study. No personal or identifiable information was collected from the participants regardless of their choice. Only completing all elements of the study corresponded to opting in. Not doing so was automatically registered as opting out, and participant data was deleted accordingly.

Participants who opted in were given a brief introduction to the study and its purpose and then assigned to one of two conditions, CAx or VR. This assignment was managed directly by the survey's built-in algorithm to ensure an evenly balanced distribution of participants between the two groups. After being assigned a condition, participants shared their prior knowledge and experiences with AM, ME, and design for material extrusion (DfME). This data helped check for a balanced distribution of participants based on prior AM knowledge by condition, informing the statistical analyses for RQ 1 and RQ 2. 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

Participants then also shared their proficiency with their assigned modality, i.e., with CAx and VR. They were prompted to describe their experience working with 3D models in their modality. It was expected that

participants had far more experience working with tools and 3D environments in CAx than in VR, due to prior CAD and CAE experiences in their engineering curriculum. As a result, measuring, acknowledging, and then synchronizing technological proficiencies in CAx and VR was necessary. Proficiency in CAx and VR was recorded on this 5-point Likert scale:

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

Next, participants in the CAx condition continued to the next step via their survey on their computers. Those in the VR condition were each given VR equipment and instructed on the next steps by the researchers. The VR equipment included a Meta Quest 2 headset and its controllers. Participants were instructed on how to wear and operate the VR equipment and then redirected to their Qualtrics surveys on the Meta Quest 2 browser.

2.2. *Developing the virtual AM environment*

Past work by the authors presented a framework for designing VR experiences for AM and DfAM contexts[78]. This research creates a virtual AM environment by adopting this framework, producing an experience that incorporates both AM process reasoning and DfAM considerations for problem-solving. The environment replicates standard 3D printing slicer programs, such as Cura, which help designers anticipate the outcomes of their builds. These slicer programs typically include estimates for the time to build completion and the amount of support material used for the build. Therefore, the virtual AM environment used in this research similarly replicated the process of slicing a part for AM and presenting such quantitative outcomes. Other real-time simulations, such as thermal modeling, finite element analysis (FEA), and fluid dynamics, were avoided. This is because the computational expense of such complex simulations renders them infeasible for VR headsets without extensive hardware support. As such, the AM environment was limited to the following virtual features, focusing on helping designers visualize and objectively evaluate the additive manufacturability of a design:

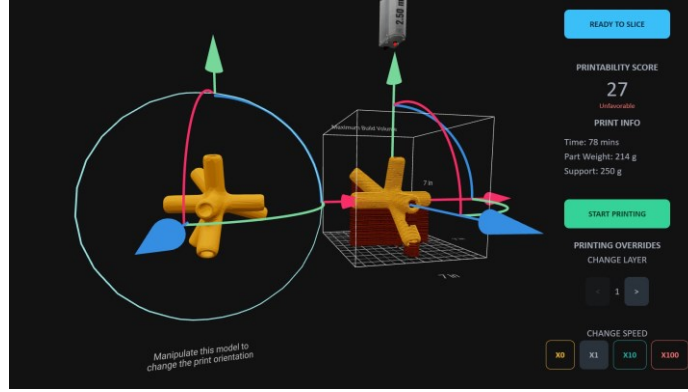
1. A 3D model of the solution submitted by the participants
2. A sliced counterpart of the solution in the chosen orientation
3. An extruder to emulate the layer-by-layer building process
4. A graphical interface to slice models, control the printer, and view the manufacturing outcomes

The designed environment was developed by the authors using openly-accessible software and libraries. A 3D web application for the CAx and VR versions was available online using standard web browsers. The WebXR JavaScript API was used to incorporate VR capabilities on the web, and the libraries used to create the 3D environment were powered by three.js^{1 2}. The VR experience was tested on the Meta Quest 2 devices only. The open-source Cura slicing engine was used to slice the 3D models. The parameters set for the slicer were for the ME process, building at 100% infill (i.e., solid part), a 2.5 mm nozzle diameter, and a 1.875 mm layer height. This engine calculated the build outcomes using these parameters every time designers changed the orientation and re-sliced a 3D model. Slicing was done behind the scenes in the browser using a WebAssembly version of the Cura engine³. Doing so allowed participants to continue interacting with the environment while the slicing engine calculated the build outcomes in the background.

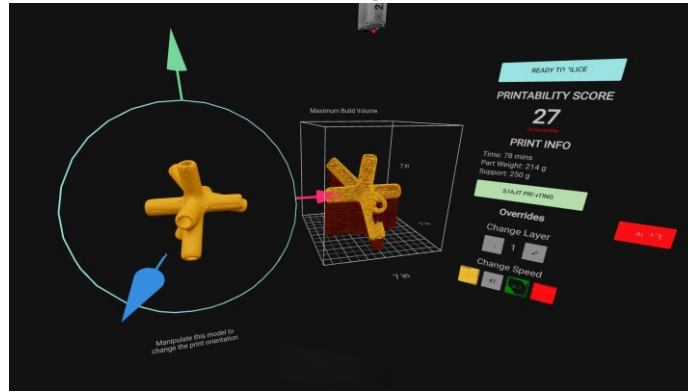
¹Website for three.js: <https://threejs.org/>

²Website for React libraries using three.js: <https://github.com/pmndrs/webxr>

³Source for cura-wasm: <https://github.com/cloud-cnc/cura-wasm>



(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 printing extruder, and a graphical interface to use the printer and view the build outcomes

To ensure that the BAM exercise was similar across the conditions, the environments were designed identically as shown in Figure 2. Users were encouraged to interact freely with a design and its environment to promote 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 to ensure that the designs and their features were manufactured at their intended scale, yielding an identical comparison of outcomes between the modalities.

2.3. The build-with-AM problem

To study the effects of immersion on additive manufacturability outcomes, designers must evaluate artifacts that require DfAM considerations, spatial reasoning, and understanding of build failure consequences. These artifacts should have geometric complexity traversing multiple planes, and designers must consider how defects affect functionality in different immersive modalities. For example, blocky or planar designs require less DfAM consideration than complex parts like fluid channels, where defects from thin walls or poor build orientation can cause leaks. This research implements these principles in creating designs for the presented study, using a template manifold presented by Diegel et al [97]. A manifold is a geometric construct that represents a network of channels that can be used to transport fluids or gases. As a part, it has an intuitive and clear functional context, and the consequences of build failures are easily understood. Manifolds can also be designed with varying numbers of channels and a spatial variety of routing paths of these channels. As such, this research used three manifold designs of varying complexity to study the effects of immersion

on additive manufacturability outcomes. The complexity of the designs was varied precisely by adding or removing in and out channels to the manifold as shown in Figure 3. The skeletal network of the designs was kept identical to control for the complexity using one variable.

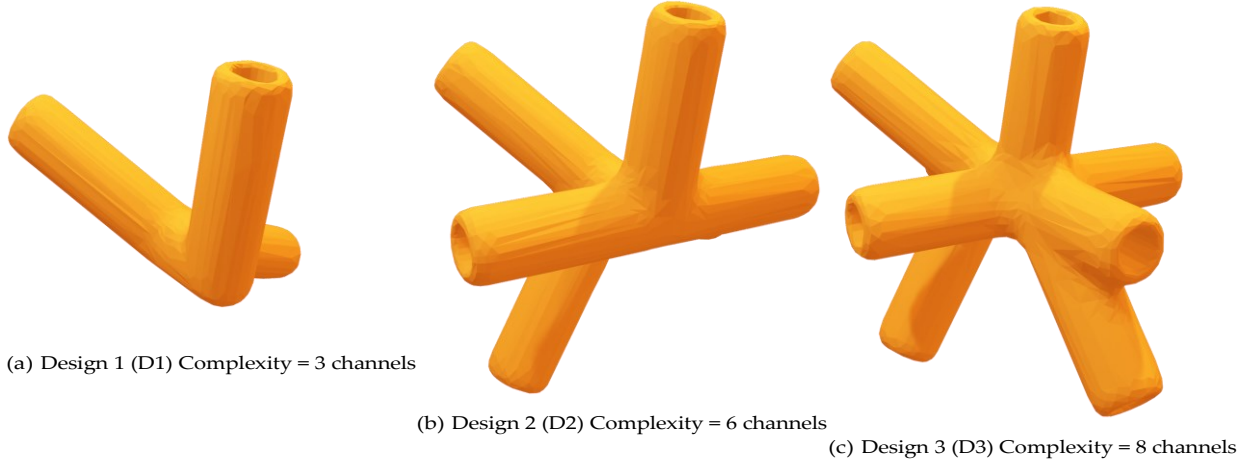


Figure 3: Showing the three designs used in the research and how they varied in complexity per the number of channels present in the design.

Participants in both conditions then immediately proceeded to a tutorial to practice working in their assigned modality and the AM environment described in Section 2.2. In this tutorial, participants manufactured one example design using their assigned modality to familiarize themselves with the new AM environment. They were required to manufacture the design in at least one new orientation and visualize the results to illustrate the features of the AM environment. Completing the tutorial prepared the participants for the BAM problem-solving exercise described in Section 2.3. For the exercise, participants were tasked with evaluating the three designs in Figure 3 and determining a build orientation for each that yielded the highest manufacturability. The designs were evaluated one at a time in a counterbalanced order to minimize sequential ordering effects[98]. From each design, the time to build completion and the support material used to produce the part determined its manufacturability. These were automatically calculated using the Cura slicing engine behind the scenes of the immersive and non-immersive design environments. These results were displayed to the participants for each design and orientation they evaluated. An overall manufacturability score was also presented to the user; this score was calculated using the build time (t) and the print-to-part mass ratio (ppr) as shown in Equation 1. The more favorable a build orientation, the higher the score, and the more manufacturable the design was determined to be. Offering this overall assessment of manufacturability emphasized the contribution of build time and support material usage in determining a favorable build orientation(s) for a design.

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

where

$$t_{\text{norm}} = \min\left(1, \frac{t}{t_{\text{max}}}\right), \quad ppr_{\text{norm}} = \min\left(1, \frac{ppr - 1}{ppr_{\text{max}} - 1}\right)$$

$$ppr = \frac{m_{\text{part}} + m_{\text{support}}}{m_{\text{part}}}$$

and

$$t_{max} = 90 \text{ mins}, ppr_{max} = 3$$

Manufacturability scores were normalized between 0 and 100 presenting a grade-like scale for the participants, primarily students, to relate to the assessment. Doing so aimed to internally motivate participants to achieve higher scores by determining more favorable build orientations. Both t and ppr were normalized between 0 and 1 and weighed equally in the calculation of the manufacturability score. Equation 1 uses t_{max} to normalize build time, where t_{max} was the generally maximum observable build time for the three designs. Similarly, ppr was normalized using ppr_{max} , the generally maximum observable print-to-part ratio. The authors determined t_{max} and ppr_{max} by building all the designs in their most unfavorable build orientations and selecting the highest values. Naturally, the highest build time was observed for the most complex and largest design, D3. The highest print-to-part ratio, however, was determined based on the range of values observed for all the designs. Although unlikely, values for t and ppr that exceeded t_{max} and ppr_{max} were deemed equally unfavorable and were truncated to their maximum values. This was done to ensure that outliers did not occur in the data and that the normalization process maintained the integrity of the scale used. Figure 4 shows the manufacturability scores determined by Equation 1 using the Cura slicing results: build time, part mass, and support usage for D3 in three different orientations.



Figure 4: Showing three different build orientations of D3 and the manufacturability outcomes calculated using the Cura slicing engine and Equation 1 for each orientation

2.4. Gauging cognitive load

Upon evaluating all three designs, participants reflected on their experience within their assigned modality. To be precise, they reported the cognitive load they experienced from evaluating the designs and determining their manufacturability in multiple build orientations. Measuring cognitive load in this research was identical to the method used in past work[77,92], namely using the Workload Profile Assessment (WPA) tool[99]. To help them report cognitive load, the WPA tool was provided as a quantitative method to gauge mental exertion. The tool considered Perceptual, Response, Spatial, Verbal, Visual, Auditory, Manual, and Speech cognitive processing needs to assess the cognitive load experienced by the participants. Participants assigned a value between 0 and 10 to represent their mental exertion on each of these eight workload profile dimensions. Compared to the Subjective Workload Assessment Technique and the NASA Task Load Index, the WPA's higher sensitivity was preferred for such quantitative assessments[100].

In the survey, participants received a text and audio description of each dimension to review, along with an example of each dimension applied in practice. These descriptions helped them gauge their cognitive load and assign appropriate values to each dimension, one at a time. The *Verbal* and *Auditory* dimensions, though not directly applicable to the BAM exercise. This is because the designed experiment did not include tasks or steps that gave verbal instruction and audio cues. The *Speech* dimension was also included under the same rationale, as the participants were not tasked to speak during the exercise. Although not applicable, this research did not check or correct for any misinterpretations of the dimensions by the participants. As such, these dimensions were still included in the survey to ensure consistency with the intended design of the WPA tool.

3. Results and analysis

This research studied the experiences of 157 participants (CAx = 75, VR = 82), who additively manufactured three designs in their assigned modality. This section presents analyses of the demographic data, the manufacturability outcomes, and the cognitive load data collected from these experiences. Specifically, Section 3.1 informs on the background of the participants, Section 3.2 the manufacturability outcomes of the three designs, and Section 3.4 the cognitive load experienced by the participants. To statistically explain the background, cognitive load, and evaluation time data, linear regression models (*lm*) were generated. Linear mixed-effects regression modeling (*lmer*) was used to statistically analyze the change in manufacturability score, build time, and support material usage. 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[101] and the Loy and Hofmann[102] procedures respectively. 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. 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.

3.1. Background analysis

Analyzing the prior knowledge of AM, ME, and DfME concepts from the 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, $b = 0.06$, $F(1,165) = 0.27$, [$t(1,165) = 0.52$], $p = 0.606$, of ME, $b = -0.04$, $F(1,165) = 0.1$, [$t(1,165) = -0.32$], $p = 0.747$, and of DfME, $b = -0.08$, $F(1,165) = 0.3$, [$t(1,165) = -0.55$], $p = 0.585$. This trend is observed in Figure 5, where participants in all the conditions reported similar prior knowledge of AM, ME, and DfME. More precisely, they generally reported having *some informal* or *formal* knowledge of each of the topics.

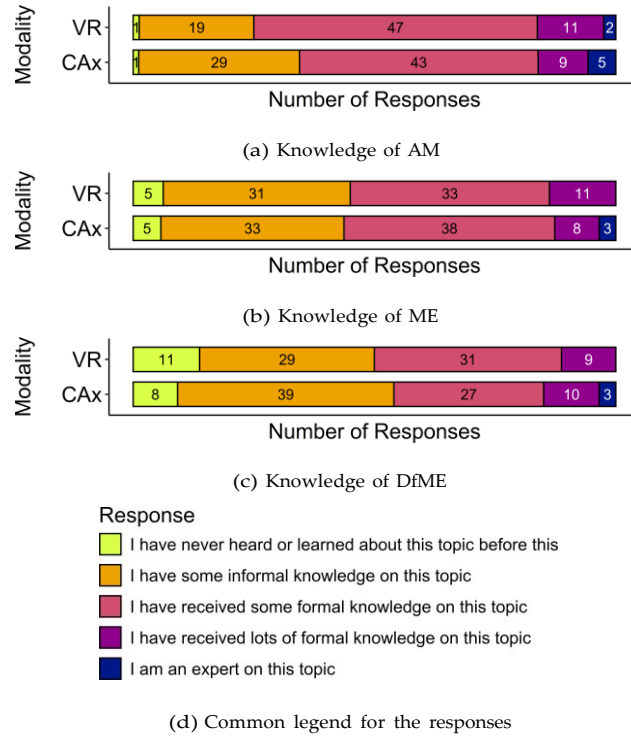


Figure 5: Presenting the distribution of reported prior knowledge of AM, ME, and DfME among the participants in the two conditions

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, $b = -0.73$, $F(1,165) = 18.4$, $[t(1,165) = -4.29]$, $p < 0.001$. That is, participants in the CAx condition were generally *extremely comfortable* or considered themselves *experts* with CAx 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 6 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[77,92].

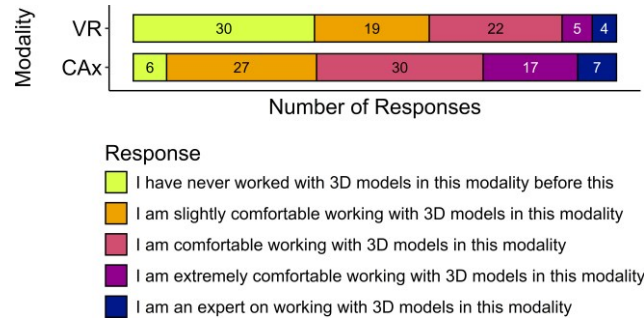


Figure 6: Presenting the distribution of reported proficiency on working with CAx and VR modalities

Table 1: Listing the general effects of each variable on each manufacturability outcome

(a) Effect of <i>Condition</i>				
Variable	Estimate	F(1, 155)	t.ratio	p.value
Score	0.44	0.40	0.63	0.528
Print Time	-0.30	0.50	-0.70	0.482
Support Usage	-4.17	1.77	-1.33	0.186
(b) Effect of <i>Design</i>				
Variable	Estimate	F(1, 312)	t.ratio	p.value
Score	-38.48	4372.76	-66.13	< .001
Print Time	52.37	9752.36	98.75	< .001
Support Usage	180.28	2220.27	47.12	< .001
(c) Interaction effect of <i>Condition</i> and <i>Design</i>				
Variable	Estimate	F(1, 312)	t.ratio	p.value
Score	2.58	4.91	2.22	0.027
Print Time	-3.91	13.56	-3.68	< .001
Support Usage	-33.71	19.40	-4.40	< .001

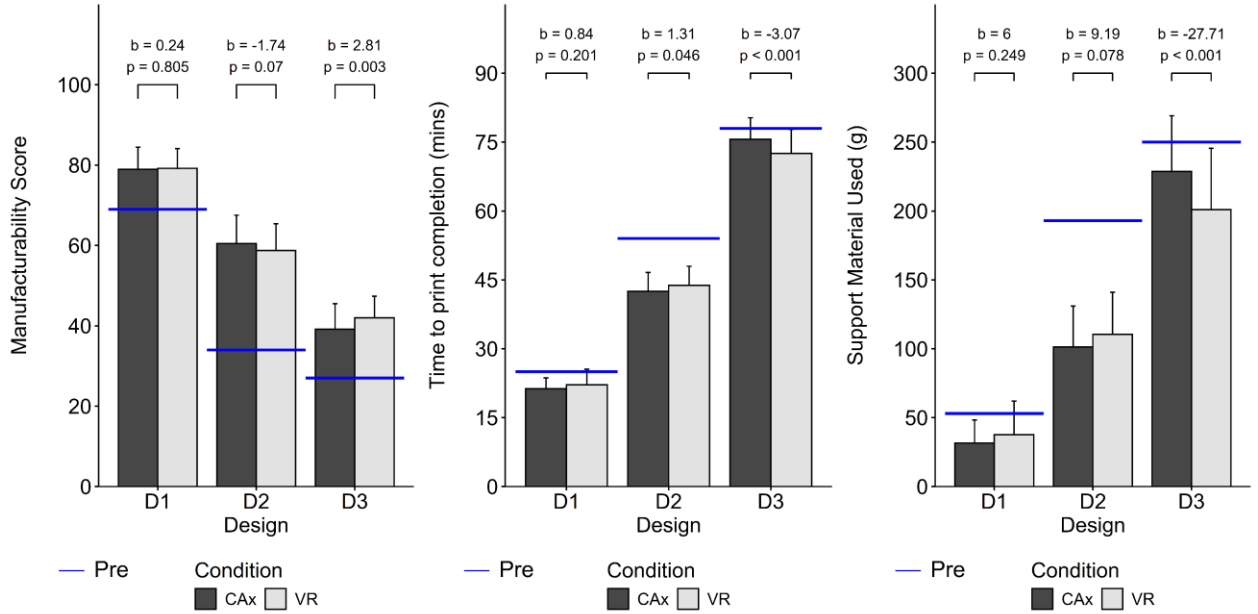
3.2. Manufacturability outcomes

Results presented in this section are observations from the data collected on the 1. *Score*: the overall manufacturability score for the designs, 2. *Build Time*: the time to build completion, and 3. *Support Usage*: the support material used. Analyzing this data helped address RQ 1, informing on the effects of immersion on the resulting manufacturability outcomes. For this analysis, *Score*, *Build Time*, and *Support Usage* were regressed on the centered variables for *Condition*, and *Design* as a covariate. *Condition* served as a between-subjects variable centered around the studied conditions: CAE = -0.5, VR = 0.5. *Design* served as a repeated measure for the within-subjects design, centered around the designs evaluated during the exercise: D1 = -0.5, D2 = 0, D3 = 0.5. 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 *Design* were considered in the analysis. These effects indicate the significance of the *change* in the manufacturability outcomes with the change in design complexity between the modalities.

The main analysis showed no significant effect of *Condition* on the *Score*, *Build Time*, and *Support Usage* (see Table 1a). This means that on collapsing the *Design* categories, the manufacturability outcomes were generally similar between the immersive and non-immersive conditions. As expected, however, the analysis did show a significant effect of *Design* on *Score*, *Build Time*, and *Support Usage* (see Table 1b). On collapsing the *Condition* categories, participants generally yielded lower manufacturability scores and higher print times and support material usage as the design changed from D1 to D3. As shown in Figure 7, this means that the manufacturability outcomes generally worsened with the increase in design complexity, as experimentally designed. Given that participants received each design in a preset orientation, *Pre* values for *Score*, *Build Time*, and *Support Usage* are also highlighted in Figure 7. These illustrations demonstrate an intentional change to each manufacturability outcome resulting from participants interacting with the designs.

Estimating a two-way interaction between *Condition* and *Design* explained how the outcomes differed between the modalities with the change in design. The analysis showed a significant effect from the interaction between *Condition* and *Design* on *Score*, *Build Time*, and *Support Usage* (see Table 1c). This means that the effects of the modality on the manufacturability outcomes changed significantly with the change in design complexity. In other words, the interaction effect suggests that as the design changed from D1 to D3, participants achieved more favorable manufacturability outcomes in the VR condition than in the CAx

condition. Pairwise comparisons between the conditions by design help explain this trend by discerning the specific effects of varying immersion on the outcomes at each design level. Figure 7a shows that participants achieved higher manufacturability scores in the VR condition than in the CAx condition for D3, the most complex design. However, the differences in the manufacturability outcomes between the modalities were not significant for D1, with an inverse emerging for D2. Figure 7b and Figure 7c suggest that this trend was attributed to participants determining build orientations in the VR condition for D3 that yielded significantly faster builds and lower support material usage. This was not observed for D1, where the outcomes were similar between the conditions, and for D2, where they were favorable in the CAx condition but not significantly so.



(a) Manufacturability score (higher is better)(b) Time to build completion (lower is better) (c) Support material used (lower is better)

Figure 7: Showing the difference in manufacturability outcomes achieved for each design as affected by the two conditions

3.3. Evaluation experience outcomes

Results presented in this section are observations from the data collected on the 1. *Evaluation Time*: the time spent determining a favorable solution and 2. *Slice Attempts*: the number of attempts made to determine a favorable solution. Analyzing this data also helped address RQ 1, informing on the effects of immersion on the designer's evaluation process and the resulting experiential outcomes. For this analysis, *Evaluation Time* and *Slice Attempts* were regressed on the centered variables for *Condition*, and *Design* as a covariate. Once again, *Condition* served as a between-subjects variable and *Design* served as a repeated measure for the within-subjects design. The results focus on each detailed effect when controlling for all other main effects in the model, with only the interaction effects between *Condition* and *Design* being considered. These effects indicate the significance of the *change* in the experiential outcomes with the change in design complexity between the modalities.

First, the main analysis showed a significant effect of *Condition* on *Evaluation Time*, $b = -0.89$, $F(1,155) = 11.26$, $[t(1,155) = -3.36]$, $p = 0.001$. This means that on collapsing the *Design* categories, participants generally spent less time in VR than in CAx to determine a favorable build orientation. The analysis also showed a significant effect of *Design* on *Evaluation Time*, $b = 2.23$, $F(1,312) = 105.19$, $[t(1,312) = 10.26]$, $p < 0.001$. Although expected, this means that on collapsing the *Condition* categories, the time spent evaluating the designs generally increased as the design changed from D1 to D3. No observable significant effect was found from the interaction between *Condition* and *Design* on *Evaluation Time*, $b = -0.67$, $F(1,312) = 2.35$,

$[t(1,312) = -1.53]$, $p = 0.126$. Figure 8 illustrates these trends, showing that participants generally spent less time in VR than in CAx to evaluate designs, which overall increased with increasing design complexity.

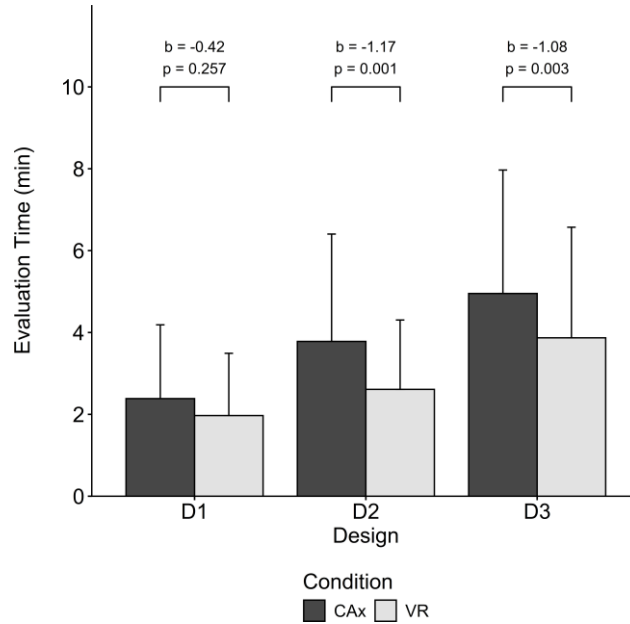


Figure 8: Showing the difference in the time spent evaluating each design as affected by the two conditions

Pairwise comparisons between the conditions by design help further discern the specific effects of varying immersion on the evaluation time at each design level. As shown in Figure 8, Participants spent significantly less time in VR than in CAx to evaluate D2 and D3 but not D1, the least complex design. This means that the main effect of *Condition* on *Evaluation Time* was observed due to the predominant effects of the modality on D2 and D3. Additionally, the time spent evaluating designs generally increased with increasing design complexity. However, the difference in evaluation time between the CAx and VR was similar for D2 and D3. This suggests that the effect of the modality on *Evaluation Time*, if significant, was similar across the designs.

Next, the main analysis did not show a significant effect of *Condition* on *Slice Attempts*, $b = -0.45$, $F(1,155) = 0.83$, $[t(1,155) = -0.91]$, $p = 0.362$. This means that on collapsing the *Design* categories, participants generally visualized a similar number of sliced orientations in both CAx and VR. However, as illustrated in Figure 9, the analysis showed a significant effect of *Design* on *Slice Attempts*, $b = 1.07$, $F(1,312) = 10.15$, $[t(1,312) = 3.19]$, $p = 0.002$. This means that on collapsing the *Condition* categories, participants generally visualized more sliced orientations as the design changed from D1 to D3. Additionally, the analysis showed a significant effect from the interaction between *Condition* and *Design* on *Slice Attempts*, $b = -1.6$, $F(1,312) = 5.69$, $[t(1,312) = -2.39]$, $p = 0.018$. In other words, participants generally visualized fewer orientations in VR than in CAx with increasing design complexity. Figure 9 illustrates these trends, showing that participants generally visualized more orientations as the design changed from D1 to D3,

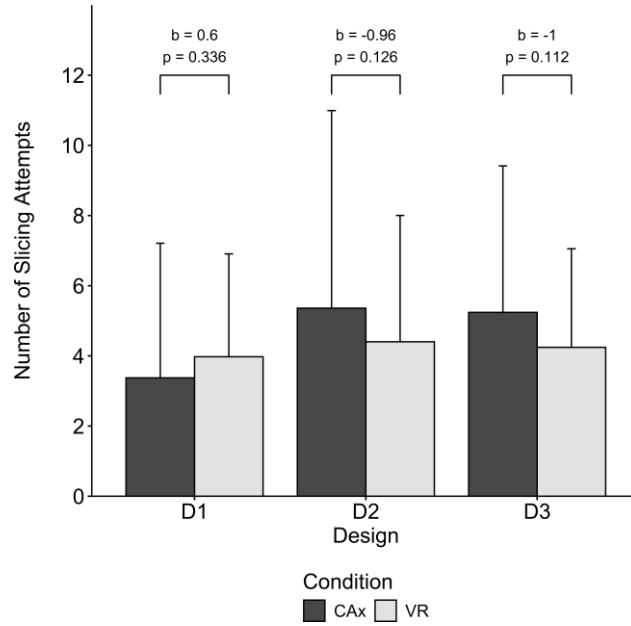


Figure 9: Showing the difference in the attempts made to slice each design as affected by the two conditions

Pairwise comparisons between the conditions by design help further discern the specific effects of varying immersion on the slice attempts at each design level. Although the interaction effect between *Condition* and *Design* was significant, the pairwise comparisons suggest no observable difference in *Slice Attempts* between the conditions for each design. Figure 9 shows that the standard deviation in the data was very high for three designs in both conditions. This suggests that pairwise statistical significance may not have been detected due to the high variability in the data. Additionally, the trend for the VR condition suggests that participants generally visualized a similar number of sliced orientations for all the designs, with similar deviations from the mean. However, the trend for the CAx condition suggests that participants visualized more orientations for D2 and D3 than for D1, with larger deviations from the mean. This suggests that the main interaction effect between *Condition* and *Design* was likely observed due to the increase in attempts with increasing design complexity in the CAx condition. Although the effect was not significant, the trend suggests higher immersion in VR may yield more consistent and focused attempts to determine a favorable solution.

3.4. Cognitive load

Analyzing this data on cognitive load helped address RQ 2, informing on the effects of immersion on the mental effort exerted from determining the manufacturability of the designs. For this analysis, the *Verbal*, *Auditory*, and *Speech* dimensions were excluded (though included in the survey, see Section 2.4) and the *remaining* five dimensions were regressed on the centered variable for *Condition*. *Condition* served as a between-subjects variable centered around the 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 10). This suggests that determining the manufacturability of a design, regardless of design complexity, in CAx and VR demands similar effort across different dimensions.

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

Dimension	Estimate	F(1, 154)	t.ratio	p.value
Perceptual	-0.52	2.39	-1.55	0.124
Response	-0.36	1.11	-1.05	0.294
Spatial	-0.35	0.84	-0.92	0.359
Visual	-0.23	0.49	-0.70	0.484
Manual	0.12	0.11	0.33	0.741

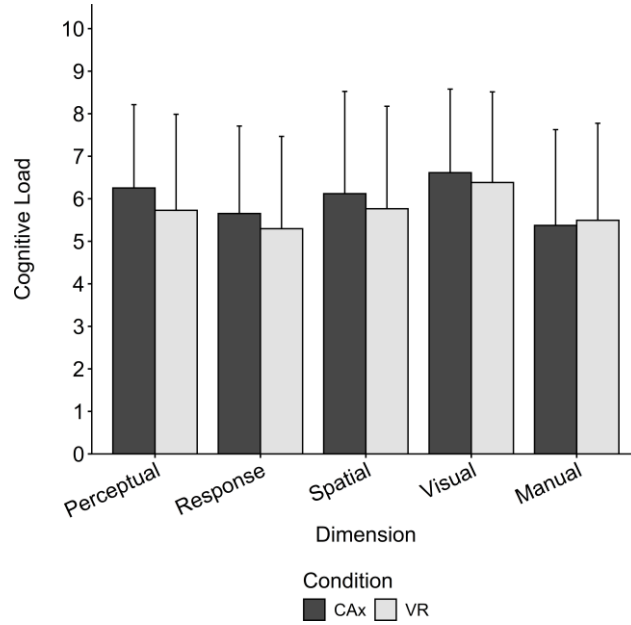


Figure 10: Showing the distribution of reported cognitive load as affected by the two conditions

4. Discussion

The goal of this research was to observe how varying levels of immersion affect the manufacturability outcomes of designs of varying complexity. The study also investigated how immersion affects the designer's approach and its outcomes when determining the manufacturability of different designs. This section first discusses the main findings from these investigations and their broader implications. It then describes the underlying mechanisms likely behind these results and discusses their significance.

4.1. Overview of the main findings

How do the differences in immersion between CAx and VR environments affect additive manufacturability outcomes when determining favorable build orientations for designs of varying complexity?

Research question RQ 1 explored the effects of varying levels of immersion on the manufacturability outcomes of an artifact designed for AM. The key finding from Section 3.2 showed that as design complexity increased, participants generally determined more favorable manufacturability outcomes in VR than in CAx (see Table 1). However, this trend was observably significant only for the most complex design, D3, and

less so for the simpler designs, D1 and D2. The consistent trend for D3 in VR presents strong implications for the effects of immersion on the manufacturability outcomes of complex designs. Compared to the participants in CAx, those in VR identified build orientations that were on average 3 minutes faster and used 28 grams less support material. Overall, these improvements produced a mean increase of 2.81 points in the manufacturability score for the design. Although this research did not allocate a monetary cost to the build time and print-to-part mass ratio, their impact on the total manufacturing cost of a part is clear[103]. Therefore, these seemingly small differences offer significant opportunities for cost reduction when mass-producing parts using ME systems. According to Singh et al.'s cost model[104] for ME processes, visualizing build orientations for D3 in VR compared to CAx would save approximately 4.61% (\$32) per part. This suggests that designs with more complexity that require sophisticated DfAM considerations may benefit further from the added immersion in VR. Overall, these findings and their implications present interesting avenues for developing tools and workflows for AM and DfAM applications, challenging the historic utility of CAx modalities. Particularly, tools with higher immersion can empower designers to make more informed improvements to the manufacturability of their designs.

How do the differences in immersion between CAx and VR environments affect experiential outcomes when determining favorable build orientations for designs of varying complexity?

Research question RQ 2 explored the effects of varying levels of immersion on the designer's evaluation process and the resulting experiential outcomes. Namely, the effects of immersion on the evaluation time, slice attempts, and experiential cognitive load were studied. Results from Section 3.3 suggest that immersion significantly affects the time spent to evaluate designs for additive manufacturability and the number of attempts required to determine a favorable build orientation. Section 3.4 further shows that the cognitive load experienced by participants was not significantly different between the CAx and VR conditions. These findings resemble the effects observed on cognitive load from previous investigations of using VR in AM and DfAM contexts[77,92]. The observed trends in the designer's evaluation process suggest that the level of immersion of an AM and DfAM experience strongly influences its outcomes. Combined with the observations from Section 3.2 that addressed RQ 1, these findings present significant implications for design workflows in AM industries. Particularly, the added immersion in VR may help designers evaluate designs faster and with precise focus, leading to more favorable manufacturability outcomes. These benefits may occur without significantly influencing the mental effort exerted by the exercise as compared to CAx experiences. Designers looking to leverage AM to solve complex design problems must evaluate multiple solutions for additive manufacturability. This is a careful, yet lengthy and tedious, process, especially when considering the functional context of the part and the consequences of build failures. As such, the findings from this research offer interesting avenues for how DfAM workflows and environments can be enhanced with immersive technologies. Notably, the results suggest that VR environments can enable more efficient decision-making processes for designers with little to no detrimental effects on their cognitive load. This is crucial for organizations looking to improve workflows that require AM and DfAM expertise during problem-solving and design generation. However, it is important to acknowledge that the effects observed were after collapsing the designs and, therefore, indicative of the overall experience. Literature suggests that the nuanced effect of *Design* on cognitive load may vary between VR and CAx with variations in design complexity[69].

4.2. *Expected underlying mechanisms*

This research observed that immersive VR significantly affected manufacturability and experiential outcomes when determining a favorable build orientation for designs of varying complexity. According to the literature, the rationale behind these effects can likely be attributed to the influence of VR on 3D perception and the designer's spatial reasoning and comprehension[52,53]. To be precise, VR likely induced a sense of presence that encouraged high levels of meaningful engagement[83,84] at low cognitive loads[72], improving short-term skills in analytics and knowledge acquisition[74,75]. With this in mind, it is important to emphasize the drastic differences in how designers interact with designs in CAx and VR environments, particularly in AM and DfAM contexts. Determining a favorable build orientation for a design requires navigating the 3D space and considering all three axial and planar directions. Such spatial awareness is crucial for intuiting the effects of the AM process on overhangs, thin walls, and support material requirements that affect the

manufacturability of a part. Therefore, immersively interacting and manipulating the designs in VR likely facilitated the mental effort and decision-making required to evaluate the designs and narrow down favorable build orientations.

In CAx, however, designers interact with the designs on a 2D screen. This limits their range of motion, visualization, and thus spatial processing which likely led to a less intuitive and more time-consuming evaluation process (see Section 3.3). To clarify, designers can freely manipulate the 3D model to any position and orientation but must do so within the confines of their viewport. The limited visualization requires more controlled manipulation on each axis to view the design in a specific orientation. In VR, however, designers are not constrained in their range of motion and can intuitively manipulate designs along multiple axes at the same time. This allows them to intuitively determine favorable build orientations, enabling a more focused assessment that narrows down on a favorable solution faster. As a result, facilitating such improved performance in VR could be due to improved layer-by-layer visualization of overhangs and inclined features, leading to more informed assessments of support usage. That said, designers in VR compared to those in CAx may have identified orientations that only slightly varied in axial rotations but still had a significant effect. Additionally, designers may have considered other factors such as thermal gradients and stresses, support removal strategies, and other build planning considerations. These are not apparent from the data collected and were not relevant to the BAM exercise but may have influenced the evaluation process and the outcomes observed. Further research is necessary to confirm these hypothesized explanations; however, the currently observable effects on manufacturing cost, time, and designer effort have significant implications for the utility of VR in AM and DfAM applications within organizations.

5. Conclusion

This research studied the use of VR in AM problem-solving to understand how immersion affects manufacturability and experiential outcomes. Designers virtually built designs with ME AM after determining the most *manufacturable* build orientation for them in either a CAx or VR environment. The results showed that as design complexity increased, participants in VR generally determined build orientations that produced more favorable manufacturability outcomes. This trend was far more significant for the most complex design (D3) than for the simpler designs (D1 and D2). Higher manufacturability of the designs was attributed to a combination of faster build times and lower support material usage. These findings suggest that the added immersion in VR may help designers determine more manufacturable build orientations for complex designs. The results also showed that immersion significantly affected the time spent evaluating designs and the number of attempts required to determine a favorable build orientation. As the design complexity increased, participants in VR generally spent less time evaluating designs and visualized fewer orientations. Additionally, the cognitive load experienced by participants was not significantly different between the CAx and VR conditions. These findings present interesting implications for organizations solving problems with AM. The most significant is that VR may encourage faster build-with-AM evaluations and solutions with favorable manufacturability outcomes without significantly influencing the mental effort exerted by the exercise. Organizational adoption of AM to achieve innovation in sustainability, cost, and time-to-market may, therefore, benefit from designers leveraging VR to produce parts faster at a lower print-to-part expense.

While there are interesting implications to these findings, certain limitations of this work must be acknowledged. This research did not observe the effects of technological proficiency on the manufacturability outcomes and the evaluation process. The influence of the participants' familiarity with the modalities on the observed effects of immersion is thus indeterminate. Future work must control for proficiency as an independent variable to investigate its effect on AM problem-solving and strengthen the findings from this research. Analyzing qualitative data through *think-aloud* exercises can facilitate an understanding of the underlying mechanisms behind the observed effects[92], including those due to engagement, proficiency, perceived liking, etc. The effect of design complexity on cognitive load was also not studied in this research. That is, the overall cognitive load experienced by participants in CAx and VR was analyzed, but not the cognitive load experienced by participants for each design. Studying how the complexity of each design affected the cognitive load will help discern the nuanced interaction between immersion and design

complexity on AM problem-solving efforts. Another key limitation of this research was due to its scope toward manufacturability evaluation only for ME. The observed results from this research may vary when considering functionally more complex processes like powder bed fusion[77]. New knowledge of how immersion affects manufacturability outcomes and experiential outcomes for other AM processes can build upon the findings of this research. 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. In addition, this research relied on rudimentary calculations to assess the manufacturability of the designs. Namely, the manufacturability score was calculated using only the sliced information from the Cura slicing engine. However, slicing engines leveraging sophisticated physics-based models of the AM process may provide a more comprehensive understanding of the manufacturability of a design. Future work must explore how a physics-based simulation of the AM process affects the manufacturability outcomes determined by designers in CAx and VR. This will present more reliable cost-benefit assessments for using VR in evaluating designs for build process planning across multiple AM processes. Furthermore, this research did not study an exercise where participants designed the parts themselves over a long time. Knowing how immersion affects the design process and the outcomes of the process would provide a more comprehensive understanding of the effects of immersion on AM problem-solving. Future work must explore the long-term effects of immersion on the design process and its additive manufacturability outcomes when designers solve an AM problem with a broader scope.

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