CSCE Annual Conference

Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)

June 12 - 15, 2019

INVESTIGATING THE USE OF VIRTUAL REALITY IN IMPROVING THE QUALITY OF DESIGN BIM FOR FACILITY MANAGEMENT

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Abstract: Building design is a complex and iterative process that requires collaboration between designers from numerous disciplines. Quality of design has a direct impact on project success especially during the operations and maintenance phase from an end-user perspective. Using modern approaches like Building Information Modelling (BIM) and Integrated Project Delivery (IPD) can help to mitigate design errors, omissions, and ambiguities. Nevertheless, there is potential to investigate how modern technologies can be used for improving the quality of design. This research aims to improve the quality of design by focusing on getting design inputs related to maintainability from relevant end-users. For this aim, the use of Virtual Reality (VR), with its potential for providing a stronger spatial understanding, is explored. A quasi-experimental approach is used to compare the performance of sixteen construction professionals who used traditional drawings and VR for providing design inputs. The participants completed pre-task and post-task questions to provide perceptions about their experience. The results suggest that participants found using VR easier and more accurate in comparison to traditional drawings. These findings are noteworthy because all the participants had substantial construction experience and used traditional drawings on a regular basis. The small sample size limits the generalizability of the results, but this study establishes as a proof of concept that VR is a viable option for getting design inputs from end-users to improve the quality of design.

Keywords: BIM, Design Coordination, Design Issue, Collaboration, Virtual Reality, Design Artifacts, Building Systems, MEP coordination.

1 INTRODUCTION

Direct and indirect design errors have a direct negative impact on the construction, as well as on the operation and maintenance of a project. Even though modern approaches such as Building Information Modeling (BIM) and Integrated Project Delivery (IPD) can support the mitigation of such errors (Lee at al. 2012; Kulkarni 2012), there is still a great research potential for investigating how the different project parties should collaborate and how can the modern technology support these efforts.

Research shows that the quality of design has a direct impact on project success and design related issues have been found to be the leading cause of delays in construction projects (Couto 2012; Correa 2016). Studies also estimate that direct and indirect design error costs 6.85% and 7.36% of project cost respectively without even considering the operation phase (Li and Taylor 2014). In order to avoid errors, omissions, and ambiguities in design, improving the design quality is important.

The lack of design inputs from relevant end-users, especially from operation and maintenance stakeholders, during the design phase leads to significant issues such as poor maintainability of the equipment, inefficient layouts, and design feasibility issues (Liu and Issa 2014). Maintainability is defined as a measure of the ease and ability to restore a defective item to its functional design state (Meier and Russell 2000). In this regard, considering spatial factors are critical in the design. As mechanical rooms in modern buildings are getting more and more complex, the costs of operation and maintenance of the buildings are increasing (Lai 2010). Maintenance has been noted as the largest building cost component (50 percent) over the building's life-cycle (Foster 2011). Optimizing the maintainability of the design has a huge impact in construction projects, and as research shows, the failure to consider the maintainability during the design stage is a critical factor leading to operation and maintenance problems (Zhu et al. 2017). Maintainability is often ignored in the design phase and in order to facilitate the next generation of advancement in facility maintenance, "design for maintenance" is required (Foster 2011).

Likewise, assessing the constructability of the mechanical design to understand the proper utilization of space and ease of carrying out building operations is a significant factor. In this regard, the lack of spatial understanding and proper communication of the issues with proposed solutions between the project participants regarding the design is a major barrier to assessing the constructability (Alalawi et al. 2015). These challenges around the maintainability and constructability of the mechanical design can benefit from collaborative approaches such as IPD and BIM and involve relevant end-users such as facility managers, maintenance workers, building operations managers during the design process to mitigate design issues. Nevertheless, dealing efficiently with BIMs in 3D environments seems to be a challenging endeavour for Facility Management (FM) practitioners. They often lack the means or expertise to leverage the models for FM during the operations phase (Cavka et al. 2017). Additionally, the limited spatial understanding provided by current tools leads to inefficient transitions between design artifacts like 2D plans and 3D models to fully understand and resolve an issue (Mehrbod et al. 2017). In this connection, Virtual Reality (VR) with its potential for providing a stronger spatial understanding of 3D environments can be a viable solution to address such challenges. Therefore, investigating the use of VR in improving the quality of design BIMs for FM is the focus of our current research. More specifically, our aim is to provide a method for getting the end-user inputs related to the maintainability and constructability of the design by comparing the use of traditional drawings and VR. For this aim, a quasi-experimental approach is used to compare the performance of the participants providing inputs using these two communication methods. The participant's perceptions and background were examined through pre-task and post-task questionnaires. The following sections outline the research approach and findings.

2 BACKGROUND

The use of 2D paper plans has been the primary means of communication in the construction industry (Gould and Joyce 2003). The value of using traditional drawings has also been well documented (Purcell and Gero 1998). With the increased adoption of BIM, 3D models containing information about intrinsic properties of the modelled objects are available to the users (Hardin and McCool 2015; Eastman et al. 2011). However, there are still obstacles in dealing with BIMs and the 3D environment by practitioners (Mehrbod et al. 2017), and therefore BIM has predominantly been used in addition to the traditional drawings for decision-making purposes.

In recent years, the construction industry has seen a steady increase in interest in using modern 3D visualization technologies like VR to improve existing work processes such as design (Wang and Schnabel 2008). VR creates an immersive virtual environment allowing users to interact with spatial orientation and digital 3D objects in real time (Warwick et al. 1993). Furthermore, VR can provide the users a stronger sense of space (Wang and Tsai 2011) and has been used to tackle a variety of design and construction problems in combination with BIM including project planning (Du et al. 2016), construction education (Rekapalli and Martinez 2007), safety training (Sacks et al. 2013), and facility management (Shi et al. 2016).

Despite these well-documented potentials of application of VR in the construction industry, its applicability for improving design quality has not been sufficiently studied in detail (Chalhoub and Ayer 2018). Moreover, there is a need for further research about what are suitable use cases for these technologies, and how they can be systematically integrated into the design workflows. This paper examines the feasibility of using VR to get design inputs from end-users.

3 METHODOLOGY

This work adopts the methodology developed for a similar study which investigated the use of mixed reality for electrical conduit construction (Chalhoub and Ayer 2018). A quasi-experimental approach is used for understanding the effect of using VR for getting design inputs from the FM end-users from a maintainability standpoint. For this aim, specific design scenarios were developed in BIM and presented to the experimental subjects in VR and on 2D drawings.

The researchers aimed to compare the effect of visualization method for providing design inputs when using traditional drawings, and when using VR. The researchers used a double-counterbalanced experimental design to make the comparison. This ensured that for a given scenario, no participant consecutively used VR and traditional drawings to avoid order-induced errors. The participants were provided with a brief explanation of the experiment followed by a pre-task questionnaire to determine their general background and perception about VR. After the experiment, the participants filled out a post-task questionnaire outlining their experience. The questionnaire was developed based on the study of using mixed-reality for electrical conduit design (Chalhoub and Ayer 2018). The methodology is outlined as a workflow shown in Figure 1.

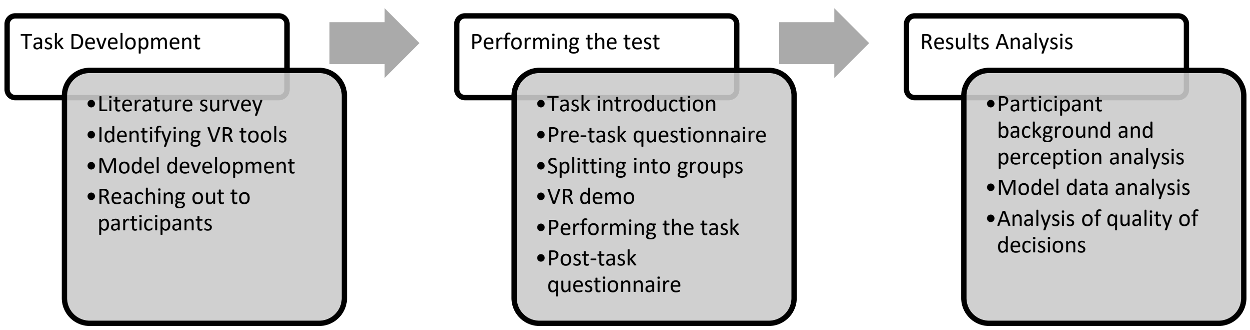

Figure 1: Steps involved in the methodology

The participants in the study were a mix of electricians, plumbers and steamfitters from the Campus Energy Center located at the Point Grey campus of the University of British Columbia in Vancouver Canada. All the participants signed an informed consent form in accordance with the University's Research Ethics Board prior to the experiment. This enabled the researchers to use and analyze the data collected during the session, including multi-angle audio and video recordings as well as pre-task and post-task questionnaires. The following section outlines each step of the implementation of our research methodology.

4 PERFORMING THE EXPERIMENTS

4.1 Experimental Setup

The experiment scenarios were designed to get inputs from the participants related to the maintainability of two sample equipment in a mechanical room. The equipment had maintainability challenges related to access in their original location and the participants were asked to determine the minimum distance by which the equipment should be relocated to make it more maintainable. The participants were informed that the sample equipment requires bi-weekly maintenance and 20-30 minutes of work duration to set a precedent for working conditions.

Scenario 1: The setup in the first scenario consisted of an expansion tank placed on the floor with its center 2 feet 6 inches from the wall. The component of the expansion tank which required maintenance was placed 9 inches from the wall. The participants were asked to determine the minimum distance by which the equipment should be relocated away from the wall to make it maintainable for the future.

Scenario 2: In this scenario, a piece of equipment requiring maintenance was placed at a height of 8 feet from the floor. The participants were asked to lower the equipment to improve its maintainability under the constraint that the working conditions do not allow the use of a ladder or a stool to improve their accessibility. The traditional drawings provided to the participants in the two scenarios are shown in Figure 2.

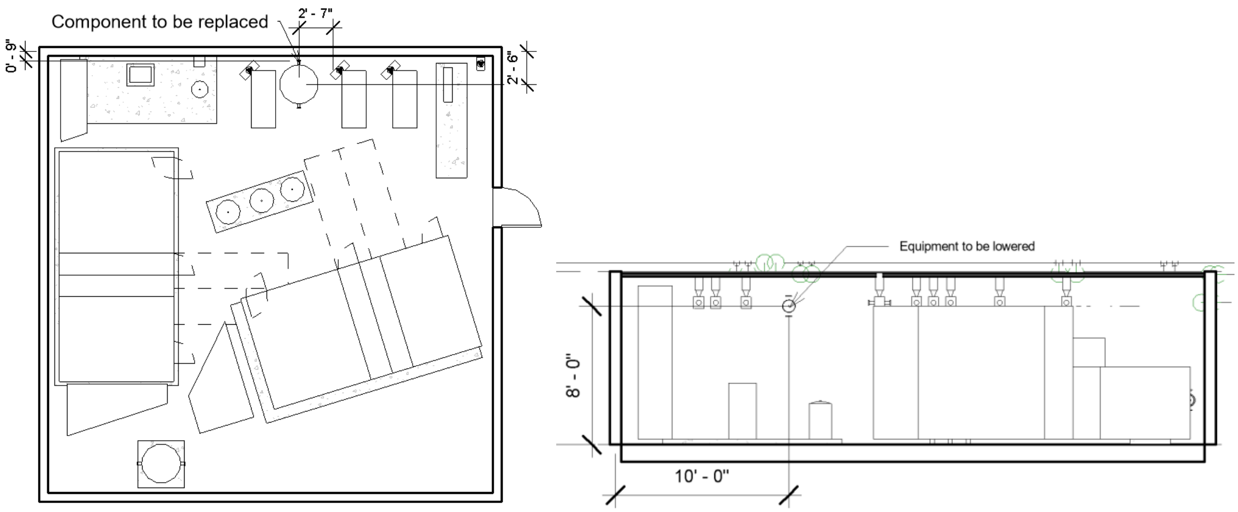

Figure 2: Traditional drawings provided to the participants for the first and second scenario respectively

4.2 Development of VR Visualization Environment based on BIM

The BIM Software "Autodesk Revit" was used for generating the traditional drawings as well as creating the VR visualization environment. For the live rendering of the BIM in VR, the researchers used "Enscape", a plugin for Revit which enabled the participants to see changes they made to the model in real-time. The researchers used HTC Vive Pro, which is a head-mounted display (HMD) device with two hand controllers capable of immersing the user in a VR environment. The device mapped the user's height in the virtual environment with the two hand controllers acting as the user's hands. The device and controllers connected wirelessly to the computer enabling the participants to freely move in the VR environment. The researchers could see the participant's VR perspective through a TV screen mirroring the device. The setup and sample rendering of the participant's view can be seen in Figure 3.

Figure 3: Setup for getting VR inputs and sample rendering of the participant's view

When the participants used VR for providing design inputs, they were given a brief 5 to 10-minute introduction to VR. During this introduction, they were guided on how to wear the HMD and use the controllers and were shown a sample living room not related to this task. This allowed all the participants to familiarize themselves with the VR environment and understand its navigation features. After the participants felt comfortable with navigating the VR environment, the model from a given scenario was loaded for them.

The participants were divided into two groups to execute this methodology. The participants in one group would start with the first scenario requiring relocation of equipment placed on the floor whereas the second group would start with the second scenario of equipment located at a height on the wall. Moreover, each group was further subdivided into two subgroups: one subgroup would start with using traditional drawings whereas the other would start with VR.

When the participants provided inputs using traditional drawings, the coordinator navigated the model in Revit to provide a 3D view. The participants could navigate the model in VR on their own using the HMD and its controllers. The coordinator made changes to the model based on the inputs from the participants. The changes suggested by the participants for both scenarios and visualization techniques were recorded by saving a new version of the model and compared with its original version.

4.3 Qualitative Data Collection

There were two types of data collected for each participant: changes to the BIM model based on the inputs provided to the coordinator, as explained above, and perception data collected in form of the pre-task and post-task questionnaires. The questionnaire responses were imported into a spreadsheet and assigned numerical values for analysis. The participants were asked to 'think-out-loud' when making their decisions which enabled understanding their reasoning through the video and audio recordings. The collected data was analyzed, and the findings are presented in the following section.

5 RESULTS ANALYSIS AND DISCUSSION

5.1 Participants

A total of sixteen industry professionals participated in this study, including plumbers, steamfitters, and electricians. A total of 63% (n = 10) had over 10 years of experience in their trade with 19% (n = 3) each having 1-5 years and 6-10 years of experience. All the participants in the study were male. Table 1 summarizes their years of construction experience and the time they spent reading construction drawings in the past year. In general, the participants had little to no experience using VR, both inside and outside of work.

Table 1: Cross tabulation of years of experience vs. time spent reading drawings in the past year

Years of construction experience	Time spent reading drawings in the past year				
	None	About 25%	About 50%	All the time	Total
<1 year	0%	0%	0%	0%	0%
1-5 years	12.5% (n = 2)	6.25% (n = 1)	0%	0%	18.75% (n = 3)
6-10 years	12.5% (n = 2)	6.25% (n = 1)	0%	0%	18.75% (n = 3)
>10 years	0%	12.5% (n = 2)	12.5% (n = 2)	37.5% (n = 6)	62.50% (n = 10)
Total	25% (n = 4)	25% (n = 4)	12.5% (n = 2)	37.5% (n = 6)	100% (n = 16)

5.2 Model data analysis

The minimum distance for the relocation of the equipment suggested by each participant was compared when they were using VR, and when they were using traditional drawings. This comparison was done for both the scenarios based on the changes suggested by the participants to the base Revit model.

The comparison of the minimum distance of relocation for the equipment in the first scenario suggested by each participant when using the two visualization methods is shown in Figure 4. When using VR for providing the inputs, the participants could physically walk around the equipment to see the available space. Participants used their controllers to check if they can reach the component to be replaced and then provided inputs for relocating the equipment. In the case of traditional drawings, they had to rely on their mental visualization of the space and previous experience to make the decision.

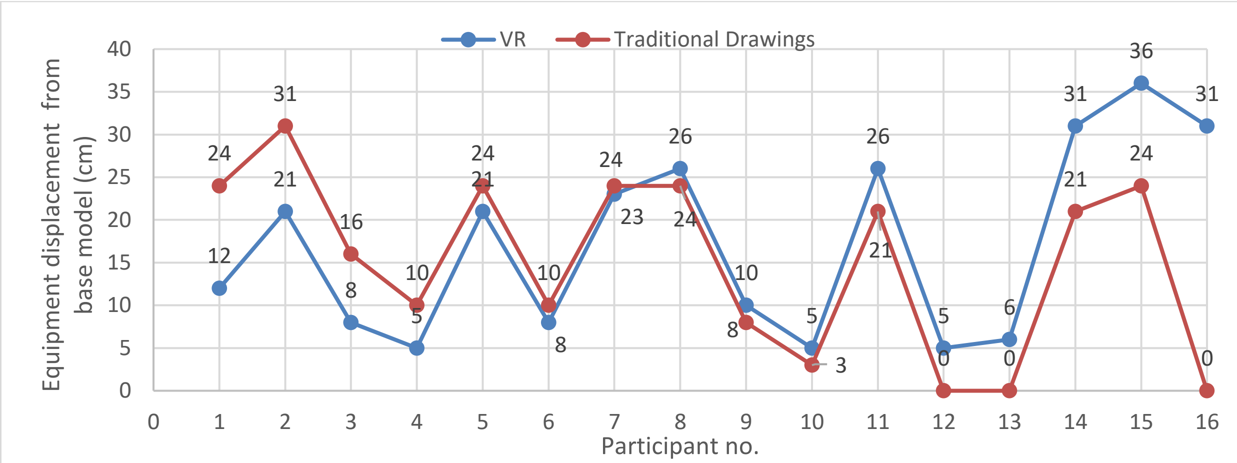

Figure 4: Displacements suggested by participants in the first scenario using both visualization methods

The results suggest that 7 participants displaced the equipment more when using traditional drawings by an average of 5.86 cm in comparison to VR. The remaining 9 participants displaced the equipment more in VR as compared to traditional drawings by an average of 8.33 cm. The results suggest that the participants could provide similar inputs using both visualization methods given a small difference (2.47 cm) between the two comparisons. The familiarity of reading traditional drawings over the years does not seem to affect the quality of their inputs in comparison to use of VR, which is relatively a new visualization technique.

The minimum distance to lower the equipment in the second scenario suggested by the participants is shown in Figure 5. The results show that most of the participants (n = 12) suggested lowering the equipment more when using traditional drawings in comparison to VR. Only one participant suggested lowering the equipment more when using VR in comparison to traditional drawings. The remaining 3 participants provided the same input when using both the visualization methods.

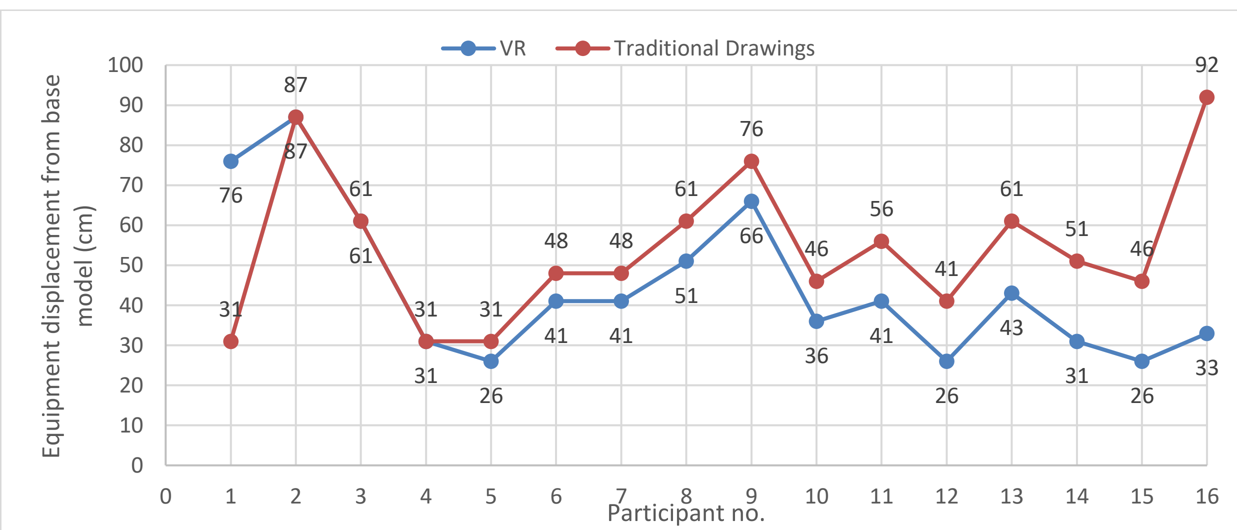

Figure 5: Displacements suggested by participants in second scenario using both visualization methods

The calibration of the participant's height in VR enabled them to see the issue in scale and in relation to the surrounding. The participants used the controllers to virtually check if they can touch and work on the equipment and then suggested how much the equipment should be lowered. In the case of traditional drawings, the participants had to rely on the mental visualization of their own height. The participants used standard heights like that of a door frame and visualized it with respect to their own height to make the decision. This mental visualization led to more conservative displacement inputs when using traditional drawings. The inputs provided from VR for decisions related to height were of a higher quality which is discussed in further detail in the following section.

5.3 Quality of decisions

The participants were asked to compare the quality of their decisions when using traditional drawings and VR for both the scenarios as a part of the post-task questionnaire. The questions inquired about ease of decision making, their perception of the accuracy of the inputs provided, and the confidence that they feel about their inputs from both the visualization methods. Out of 16 participants, 11 participants answered these questions. The responses to these questions for the first scenario are shown in Table 2.

Table 2: Responses to questions related to the quality of decisions for the first scenario

Questions	Strongly disagree/ (1)	Disagree / (2)	Neutral / (3)	Agree / (4)	Strongly agree / (5)
It was easier to make design decisions using Virtual Reality than traditional drawings	0%	0%	18% (n = 2)	45% (n = 5)	36% (n = 4)
I can make more accurate decisions using VR than using traditional drawings	0%	0%	36% (n = 4)	55% (n = 6)	9% (n = 1)
How confident do you feel about giving your answer from VR to the designers for making design changes (1-5 scale)	0%	0%	9% (n = 1)	55% (n = 6)	36% (n = 4)

The results show a strong agreement among the participants regarding the ease of decision making when using VR in comparison to traditional drawings with only 2 participants having a neutral outlook. None of the participants disagreed with the ability of VR to provide more accurate and realistic design inputs. The participants had a confidence rating of 4.27 (out of 5) based on the weighted average of their inputs provided using VR. The results suggest that VR is a viable option for providing design inputs from the end-user perspective. The participants were asked the same questions after performing the task related to the height of the equipment in the second scenario. Their responses are shown in Table 3.

Table 3: Responses to questions related to the quality of decisions for the second scenario

Questions	Strongly disagree / (1)	Disagree / (2)	Neutral / (3)	Agree / (4)	Strongly agree / (5)
It was easier to make design decisions using Virtual Reality than traditional drawings	0%	0%	9% (n = 1)	55% (n = 6)	36% (n = 4)
I can make more accurate decisions using VR than using traditional drawings	0%	0%	27% (n = 3)	64% (n = 7)	9% (n = 1)
How confident do you feel about giving your answer from VR to the designers for making design changes (1-5 scale)	0%	0%	0%	64% (n = 7)	36% (n = 4)

Except for one participant, all the participants agreed that decision making was much easier when using VR. Additionally, none of the participants disagreed with the view that VR can provide more accurate design inputs in comparison to traditional drawings as observed in the first scenario. The confidence rating of participants about their decision made in VR was comparatively higher to the first scenario (4.36 out of 5) based on the weighted average. The calibration of the user's height in VR and the ability to see the location of the hands via the hand controllers led to higher ratings from the participants for all the three metrics in the second scenario.

5.4 Perception

This study explored the perceptions of the construction professionals with regards to the use of VR for providing design inputs to improve the quality of design. Pre and post-task questionnaires were used to understand these perceptions and identify any shifts in perception that may have occurred for these 16 participants.

5.4.1 Pre-task questionnaires

The pre-task questions assessed the anticipation of the participants about their experience of using VR in comparison to traditional drawings for providing design inputs. The responses to the pre-task questionnaires are shown in Table 4 below.

Table 4: Sample pre-task questionnaire responses

Questions	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Virtual reality can completely replace traditional drawings for making design decisions	6% (n = 1)	13% (n = 2)	56% (n = 9)	13% (n = 2)	13% (n = 2)
Virtual Reality will be easier to use than traditional drawings for the purposes of making design changes and decisions	0%	6% (n = 1)	56% (n = 9)	25% (n = 4)	13% (n = 2)
I am looking forward to eliminating the use of traditional drawings and relying only on digital means of design communication	0%	25% (n = 4)	44% (n = 7)	25% (n = 4)	6% (n = 1)

The results indicated that the participants differed widely in their view of whether VR can completely replace traditional drawings for making design decisions. Their enthusiasm towards relying only on digital means of communication also is varying with most of the participants choosing to be neutral on the topic. The least disagreement was shown in their perception of the ease of use of VR for providing design inputs wherein only one participant disagreed with the overall view.

5.4.2 Post-task questionnaires

The participants completed a post-task questionnaire after using both traditional drawings and VR for providing design inputs in the two scenarios. The responses indicate that, in general, all the participants find VR as an effective mean for providing design inputs. The response related to using VR rather than traditional drawings for making design decisions showed mixed responses. This is understandable given the familiarity of the participants for using traditional drawings. In the feedback captured through audio recordings, the participants suggested that the use of VR in combination with traditional drawings for providing design inputs will be most beneficial. A total of 88% (n = 14) participants felt that inexperienced individuals will find VR most beneficial to provide their design inputs. The ease of use of VR makes it easier for individuals with limited experience to visualize the environment and provide inputs. The responses from the participants for the post-task questionnaire can be seen in Table 5.

Table 5: Sample post-task questionnaire responses

Questions	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
With Virtual Reality, I can effectively make design decisions without the need for traditional drawings	0%	0%	19% (n = 3)	56% (n = 9)	25% (n = 4)
I would rather use Virtual Reality than traditional drawings for making design decisions	0%	13% (n = 2)	44% (n = 7)	25% (n = 4)	19% (n = 3)
It would be easier for inexperienced individuals to make design decisions with virtual reality than with traditional drawings	0%	0%	13% (n = 2)	50% (n = 8)	38% (n = 6)

5.5 Limitations

The experimental design of the study is presented as a proof of concept for the use of VR technology for getting design inputs compared to traditional means of using drawings. The mechanical room used for the test was a simplified representation of complex mechanical rooms. The participants were asked to provide their design inputs for relocating the equipment in the two scenarios without considering the impact on other systems part of the room. Furthermore, the sample size is relatively small to make industry-wide generalizations. Future studies aiming to incorporate the impact of other systems in the room and generalize the findings of this paper can take these factors into consideration.

6 CONCLUSION

In this study, the use of VR for getting design inputs from end-users to improve the quality of design was explored. An experiment was designed to get maintainability related design inputs from construction professionals using traditional drawings and VR. The performance of the participants using the two visualization methods was compared. Moreover, the perception of the participants before and after use was studied. The results suggest that the participants found using VR easier to provide design inputs especially for tasks related to deciding height because of the calibration of the user's height in VR. Moreover, the spatial understanding provided by VR helped the participants to make more accurate decisions from their perspective in comparison to using traditional drawings. The participants noted that the use of VR in combination with traditional drawings can provide the most insightful inputs to improve the quality of design.

This study demonstrated the potential value for the use of VR to provide design inputs over traditional drawings by using a simplified mechanical room model and construction professionals. The findings are limited by the sample size of the participants and the complexity of the design problem. Future research will focus on the increased complexity of the design problem wherein the impact on other systems in the mechanical room is addressed. Additionally, other use cases where providing inputs using VR can be useful will be explored.

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