



EVALUATING MULTIUSER AUGMENTED REALITY FOR 4D CONSTRUCTION PLAN REVIEW

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Abstract

Construction plan review meetings benefit from visualizing 4D construction models using various media such as Immersive Technologies (ImT). However, ImT, such as Augmented Reality (AR), have not been thoroughly investigated for their effects on collaborative reviews. This paper aims to evaluate the effect of using a developed 4D Multiuser AR (4DMAR) application on task performance using a comparative study against a screen-based environment. A questionnaire and observational data were used to measure the participants' experience and preferences. Sixty-two students found the interaction in both environments easy but perceived 4DMAR as more interactive and suitable for collaborative plan reviews.

Introduction

Construction projects are highly complex and dynamic and involve many interdependencies between activities (Sterman, 1992). In addition, almost every construction project is unique in design, materials, construction methods, and the surrounding environment. Therefore, many challenges exist during the construction process that take time to identify in the design process. For instance, planning the site logistics layout, especially in congested areas, can be difficult without simulating the construction process.

Incorporating visualization techniques to enhance the planning process for a construction project can be highly beneficial. As an example, Guo et al. (2017) found that visualization can enhance the identification of safety hazards before and during the construction phases of a project. It also increases our efficiency in dealing with complicated issues requiring high cognitive levels (Johnson, 1998). The most appropriate visualization method will depend on several factors, including the scope and depth of the project, the experience levels of the team members involved in the planning process, and the available resources. By carefully considering the unique needs of each project, it is possible to identify the most effective visualization methods for enhancing planning and achieving the required results.

While traditional 2D drawings and 3D models can provide a valuable visual representation of aspects of the

construction process, they may not always be the most efficient way to navigate the sequence of construction activities. Adding time as another dimension in a 4D model enables the visualization of the construction sequence. Visualizing the construction sequence can provide insights into unforeseen problems and the site layout, considering the transportation cost (Bortolini et al., 2019). Hartmann & Fischer (2007) provided a case study where 3D/4D models support constructability reviews and convey general information to all stakeholders. The models were used to convey the details of the construction plan to all stakeholders, even those who are not engineers, and it is one of the examples of using 4D models in the construction industry. 4D modeling can also yield better coordination between disciplines (Staub-French & Khanzode, 2007).

Immersion affects how people interact with the environment, including increased attention (Silva et al., 2017). One of the most promising options to improve construction project planning is to use ImT, such as AR (Davila Delgado et al., 2020). This can be especially valuable in complex construction projects with many stakeholders with diverse perspectives and interests. Using AR can improve experts understanding of the design and construction of a project (Meža et al., 2015). Virtual Reality (VR) can visualize 4D construction plans and support constructability analyses (Haymaker & Fischer, 2001; Al-Adhami et al., 2018).

Immersive technologies offer new possibilities for multi-user interactive visualization to review construction plans. However, collaborative reviews in AR have not been thoroughly studied. This study aims to assess the impact of immersive, multi-user AR on task performance when reviewing 4D construction plans. To accomplish this, several objectives were pursued. First, a multi-user AR solution, termed 4DMAR, was developed to visualize 4D models through head-mounted AR headsets. Subsequently, a quasi-experiment was conducted to evaluate the effectiveness of the 4DMAR solution in facilitating multi-user construction plan reviews. This experiment involved conducting interactive multi-user sessions and employing various data collection methods. The study involved 62 participants who completed a questionnaire to collect perceptual data on their overall

experience and preferences along with the collected observational data.

Related Works

Several papers that have presented an AR construction application were identified (see Table 1). In general, two different types of AR displays were used, including screen-based, such as using the camera on a tablet PC and projecting augmented information on the screen, and head-mounted, where augmented content was directly placed in the user's view of the space. Very few examples of head-mounted AR were identified in the literature.

Lin et al. (2020) developed a prototype for using screen-based AR and 4D modeling to enhance the operations of a tower crane. The paper did not provide an assessment of the usability of this prototype. However, it demonstrated how AR could translate 4D model information into showing the lifting path sequence. Lin et al. (2019) developed another prototype for construction progress monitoring using AR to show the construction sequence.

Another early study demonstrated a detailed approach to visualizing construction activities using AR and GPS (Behzadan & Kamat, 2013). This research provided a technical evaluation and demonstration of how a platform could be developed to visualize objects in their future physical location. The paper showed the possibility of a multiuser interactive AR construction model. Wang et al. (2014) used a 4D AR model to discuss construction issues through multiple stakeholders in a collaborative environment. The model helped visualize a natural gas plant's complex construction. The presented model was interactive and provided insights into safety issues. One of the comparative examples is the one provided by Kim et al. (2012). They provided an interactive multiuser and immersive AR tool to visualize equipment operation on the construction site. The tool provides multiple pieces of equipment to visualize different scenarios. Lin et al. (2015) provided an example of using screen AR for site plan review in a multiuser environment. The paper evaluates the use of AR using the time spent reviewing the plan. Also, it provides some perceptual feedback using a user-experience questionnaire.

Different evaluation approaches have been used to consider the impact of using AR/VR in design reviews. Most studies used questionnaires focusing on the user

experience regarding comfort or how they enjoyed the experience. For example, Amrollahibuki (2019) used a questionnaire to evaluate the user's overall experience. One of the assessment methods that can be used is to compare the learning outcomes between the use of immersive technologies and traditional environments. A similar example was provided by Wolfartsberger (2019), where added flaws to the design were used to evaluate the VR value. However, this application was specific to electric equipment (power units), and flaws were quantified based on the design elements being reviewed, such as ergonomic or design issues. In the construction context, this can be difficult to quantify and categorize due to the lack of design standardization, which makes this method difficult to apply. Wang et al. (2022) used a weighted evaluation metric to control an assembly process's AR experience. For example, the presented metric can evaluate how the users felt about manipulating the objects.

Two gaps were identified throughout the literature. First, many previous examples provided concepts or prototypes of using AR for construction planning; however, these were often confined to proof-of-concept implementations due to technological limitations of early AR devices like poor computing performance, inaccurate synchronized alignment of objects, and lack of multi-user capabilities. With recent advancements, building fully functional multi-user AR environments is viable. These technologies include advanced alignment methods that use image recognition and the increased performance of AR/VR headsets to handle larger amounts of information. Second, most previous examples were limited to feedback about user experience, with limited applications of an objective evaluation. Evaluating the methods is essential to consider this technology construction planning. Therefore, a comprehensive example of using AR as a review environment for collaborative work was evaluated in this experiment in the context of construction planning.

Developing A 4D Multi-User Augmented Reality (4DMAR) Visualization System

The 4D Multiuser Augmented Reality (4DMAR) system was developed following the framework in Table 2. Some elements in the framework, such as implementing

Table 1: Research Trend Summary

Source	Technology	Application	Assessment	Multiuser
Lin et al. (2020)	Screen AR (Markerless)	Equipment Operation Monitoring		
Lin et al. (2019).	Screen AR (Markerless)	Construction Progress Monitoring		
Behzadan & Kamat (2013)	Head Mounted AR (Marker)	Construction Visualization		✓
Wang et al. (2014)	Screen AR (Marker)	Construction Control		
Kim et al. (2012)	Head Mounted AR (Marker)	Equipment Operation		✓
Lin et al. (2015)	Screen AR (Markerless)	Site Plan Review	✓	✓

Autodesk Navisworks® and Autodesk 3ds Max®, are adopted from Boton (2018).

The primary use case was to enable multi-user, real-time visualization and interaction with 4D models in an augmented reality context. Key functional requirements included multi-user synchronization of the 4D model state, navigation of the model sequence using a time slider, and physical exploration of the model. The system architecture centered around utilizing the Autodesk Navisworks® platform for 4D building modeling capabilities, the Unity game engine for multiuser networking and augmented reality functionalities, and the Meta Quest Pro headsets as the AR delivery devices. Autodesk Navisworks® was selected for its robust 4D modeling toolset and integration with common BIM authoring tools. Unity provided a framework for spatial computing applications along with its multi-platform deployability. The Meta headsets offered a powerful option for an AR multiuser experience using the passthrough functionalities.

The system development started with creating the 4D model using Autodesk Navisworks®. Next, the model geometry was optimized using Autodesk 3ds Max® to reduce the polygon count. The next three steps were performed to develop the interaction in the Unity

Realtime Development Platform, and then the app was deployed to the Meta Quest Pro.

A 4D model of a real constructed project with construction additional flaws added was developed. The purpose of adding flaws was to enable conversation elements and determine whether those flaws were noticed and in which review environment. The building used for this activity is a service and office building. The building consists of three floors and a basement. Only the structural and architectural models were used in the 4D model. The excavation tasks were included, and some exterior scaffolding for the masonry facade was added. Fifty-seven activities were represented in the 4D model. Figure 1 illustrates four major stages of the project, from excavation to completion. The first image on the top left shows the excavation activities of the basement and the footings. The top right image illustrates the finished basement, some steel erection activities, and the start of one concrete floor activities. The bottom left image shows the façade activities with the scaffolding highlighted in yellow, and the last image shows the completed project.

Table 2 AR Experience Development Process

Steps	Resources	Description
1. Build the 4D model	<ul style="list-style-type: none"> Autodesk Navisworks® 	<i>Autodesk Navisworks® was used to build the 4D model.</i>
2. Optimize the 3D models	<ul style="list-style-type: none"> Autodesk 3ds Max® 	<i>The geometry of the 3D models was optimized for enhanced performance in the AR view.</i>
3. Customize the AR environment	<ul style="list-style-type: none"> Unity Realtime Development Platform Oculus Package Manager 	<i>The AR experience was enabled using the passthrough feature. The alignment of the model for multiuser was developed using a Shared Spatial Anchor (SSA)</i>
4. Create interactivity features	<ul style="list-style-type: none"> Unity Realtime Development Platform Oculus Package Manager 	<i>Interaction features and User Interface (UI) were developed using Unity and Oculus UI.</i>
5. Build the multiuser platform	<ul style="list-style-type: none"> Unity Realtime Development Platform Photon Unity Networking 	<i>Photon Unity Networking was used to create rooms for multi-users.</i>
6. Deploy the app	<ul style="list-style-type: none"> Meta Quest Pro 	<i>The app was deployed on multiple headsets.</i>

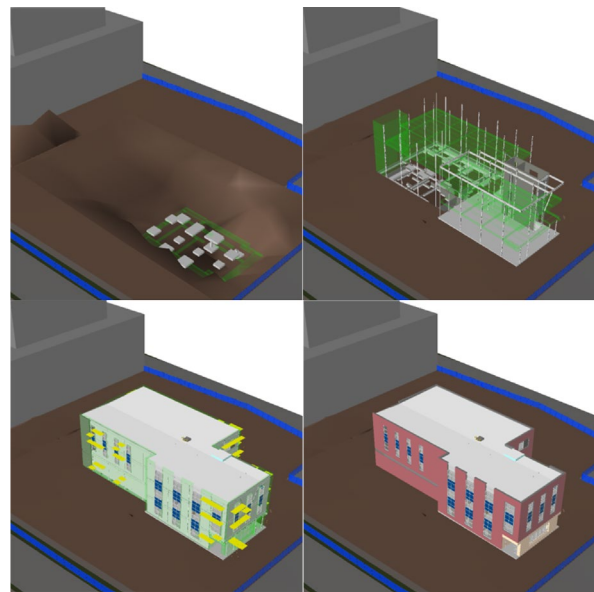


Figure 1: 4D Model Major Stages

The 3D geometry of the model was optimized to increase the system's performance by reducing the number of polygons. Reducing the number of polygons in a scene can increase the Frames Per Second (FPS) for displaying content in the AR head-mounted display. The Meta Quest Pro headsets perform better within a certain number of triangle counts or polygons, which are around 750k-1m triangles, to allow acceptable FPS as recommended by Oculus (2022). Oculus suggests that a minimum of 72 FPS should be targeted for optimal content viewing. Therefore, the model was optimized to increase the system's performance by reducing the number of polygons using tools incorporated into Autodesk 3ds Max®. However, this does cause quality reductions in the model for visualization, in which some elements lost

some features like missing or reduced quality of a geometry. Because the model size was small when viewed in the physical environment, this issue was insignificant and did not affect the visualization of the building elements.

Customizing the environment was performed by adjusting the Unity Realtime Development Platform settings making it compatible with the Meta Quest Pro. The AR experience was enabled by using the passthrough video feature of the display. The alignment of the model for multiuser was developed using a Shared Spatial Anchor (SSA). Other alignment methods were considered, such as manual alignment using the controller. However, SSA provides a fast and relatively accurate geospatial positioning. The main interaction features added to the system were time navigation using a slider and moving the model using pinching by the controller side button. The slider was linked to an animation file that contains the construction schedule. However, using the animation file adds a limitation if there are future schedule changes, which should be addressed in the future development of the 4DMAR. The collaborative environment was built using the Photon Unity Networking Platform. The platform enables multiple users to enter the same rooms and share the same synchronized 4D model. The 4DMAR was tested on three different headsets simultaneously, two Meta Quest Pros and one Meta Quest 2, and it performed adequately. Figure 2 shows the built application of the AR review environment.



Figure 2: Examples of Users in the 4DMAR Application, each looking at a synchronized model instance

Assessment of the 4DMAR

To assess the performance of the 4DMAR, a quasi-experiment was performed. The assessment started with designing an experiment to reflect the assessment approach and a questionnaire to measure the participant's perception of the experience. Three pilot tests were performed to adjust and refine the experiment design.

The current practice used for reviewing 4D construction models in the industry is typically using a monitor(s) or a

projector(s), referred to as a screen-based method in this study. Therefore, this research compared the 4DMAR as a review environment to the screen-based review, providing a shared resource in both options, see Figure 3. This led to the question: Can 4DMAR provide a suitable environment for reviewing 4D construction plans compared to screen-based reviews?

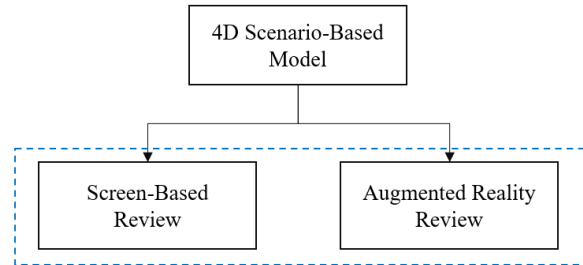


Figure 3: Evaluation Approach

The ability to review the 4D models was performed on two platforms: 1) the screen-based (SB) using Autodesk Navisworks® and 2) AR using 4DMAR. The laptop screen was rear-projected on a 6'x8' screen to ensure an appropriate view for a pair of participants. Similar interaction features, timeliner, and navigation were used in both environments. Also, to maintain the consistency of interactions between the two environments, the toolbar of Autodesk Navisworks® was hidden, and only the Timeliner was enabled in the screen-based 4D model review.

An experiment path was designed to test both environments, as seen in Figure 4. Since this is a multiuser activity, two participants performed each experiment. This was a deliberate choice to create a manageable multiuser environment while minimizing technological and data collection complexities that could arise with larger groups. To test whether the order of the experiment would affect the overall preference, another path was added, switching both environments, and it was annotated as path B. After each review session, a questionnaire was answered by both participants separately.

Each path started with a script that introduced the purpose of 4D modeling and what kind of flaws are usually found in a 4D model. It also introduced the design of the building being reviewed and how to interact with both environments. However, the script did not ask the participants to complete a specific task while reviewing the model and left the review open for participants based on the mentioned flaws.

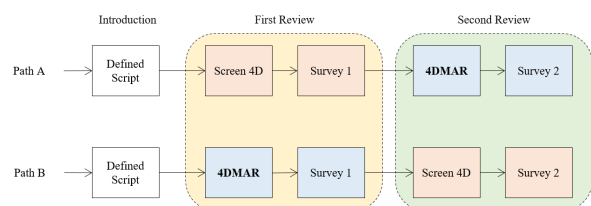


Figure 4: Experiment Paths

A questionnaire was designed to collect perceptual data. The questionnaire was answered individually after each review environment to address the second research question of whether the order of using the AR would affect the preference. The questionnaire was designed to test three factors: 1) overall experience, 2) interaction experience, and 3) overall preference between the two environments. Both usability and interactivity questions were rated on a 6-point Likert scale since participants will answer this for both environments and to make the comparison more distinctive. However, the overall preference includes both environments in the same questions, and a no-preference choice was added to reduce bias. More details are provided in Table 3.

Table 3: Questionnaire Design

Collected data	Survey	Description	Question type
	<u>1</u> <u>2</u>		
Background information	✓	Collected information includes sex at birth, industry experience, AR/VR experience, and Autodesk Navisworks® Experience. Collected as a subpart of survey 1 to minimize the number of surveys.	Open-ended questions and multiple choice
Overall experience	✓ ✓	The rating included comfort, familiarity, enjoyment, ability to find flaws and opportunities, and need for technical support.	Likert scale Strongly agree – Strongly disagree.
Interactivity	✓ ✓	Rating the interactivity experience of the interactive features, time navigation, model exploration, and ability to interact with a teammate.	Likert scale Easy – Hard
Overall preference	✓	The last part of Survey 2 asked about the overall preference	Likert scale AR – no preference (mid) – Screen-Based

Figure 5 shows the two review environments' physical spaces. The blue boundary represents the guardian set for all headsets. During pilot testing, system functionality was assessed, along with clarity and adequacy of the questionnaire and the experiment flow. The pilot was performed on the apparatus of the experiment and how the flow of the other experiment was maintained.

Results and Discussion

Questionnaire Results

Sixty-two participants were involved in this experiment; 16 groups followed Path A, while 15 groups followed Path B. Consent was obtained from all experiment participants. Each group had two participants. The participants included 23 female and 39 male participants.

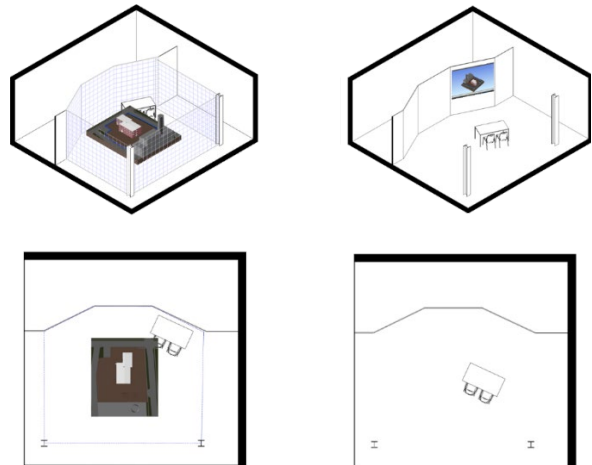


Figure 5: Review Environments Physical Space (left is 4DMAR and right is screen-based)

Forty-seven (76%) participants have had an internship experience in the construction industry. Most participants (82%) had limited experience using Autodesk Navisworks®, having used the software once or twice. In addition, most participants (71%) have experienced AR/VR headsets before, but a majority only experienced them once or twice.

Six questions were answered for both the SB and AR reviews to evaluate the user's overall experience with the review. All responses slightly favor AR as a review environment for the overall experience (see Figure 6).

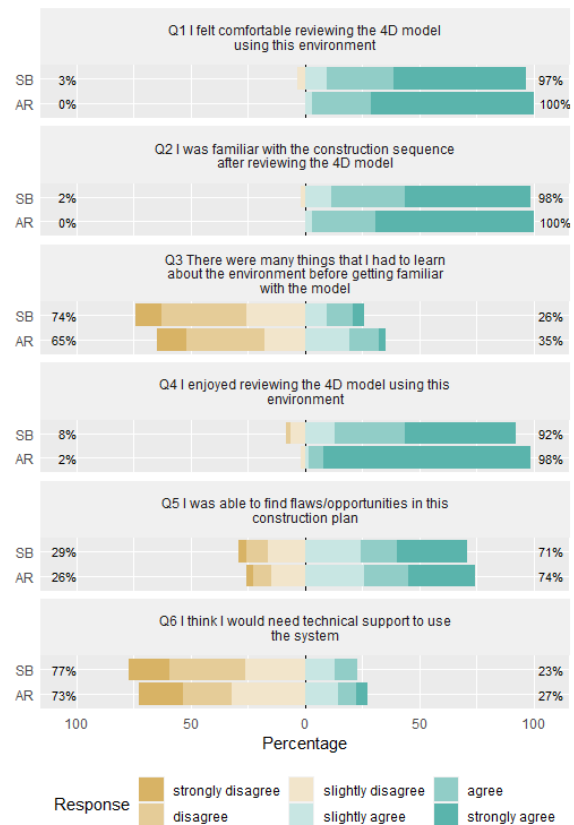


Figure 6: Overall Experience Response, Screen-Based (SB) top bar vs Augmented Reality (AR) bottom bar

Only one result showed a majority preferring AR: question 4, in which most participants strongly felt they enjoyed the AR reviews.

Three questions were used to rate the interactivity features in both environments. Similarly, the overall response slightly favors AR. Participants typically felt that it was relatively easy to interact with both environments. However, the questions were particular to the shared interaction features. See Figure 7 for a graphical representation of the Likert scale.

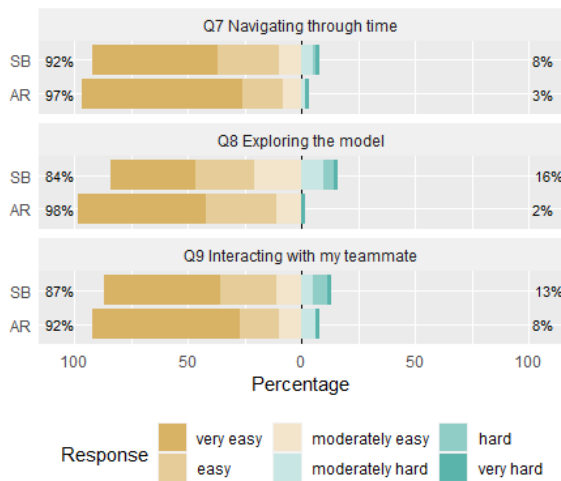
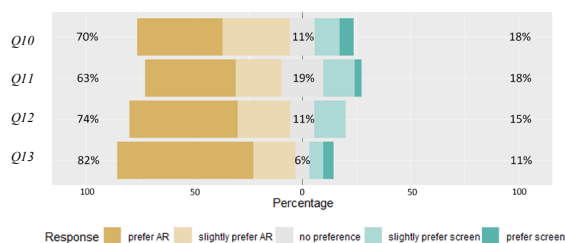


Figure 7: Interaction Response, Screen-Based (SB) top bar vs Augmented Reality (AR) bottom bar

Lastly, each participant answered four questions on their overall technology preference after using both environments (see Figure 8). This data is further analyzed in the next section, considering the experimental path. Participants indicated they would prefer AR to be used in their next review in Q10. They perceive AR as having more potential to be used in the future, as answered in Q11. Also, in Q12, they perceive AR as giving them a stronger sense of depth, spatial awareness, and realism. In the last question, which helps answer the collaboration question, 63% of participants felt AR is more suitable for collaborative reviews, 19% had no preference, and 18% preferred screen-based reviews.



- Q10: Next time, I will review the 4D model using:
 Q11: In your opinion, which environment has more potential for construction plan reviews in the future?
 Q12: Which environment provided a stronger sense of depth, spatial awareness, and overall realism for the models being presented?
 Q13: Which environment do you think is better suited for collaborative work and group activities?

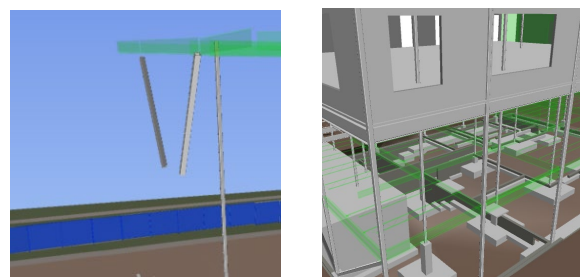
Figure 8: Preference Responses, Screen-Based (SB) vs. Augmented Reality (AR)

Observational Data

While performing the experiments, observational data were collected using video recordings. In addition, videos were analyzed to study participants' behavior using the two environments.

The experiment's script outlined the goal of the 4D modeling reviews, but there was no emphasis on participants recording any flaws or opportunities in the construction plan. This was intended to reduce the pressure on participants in a new environment regarding finding flaws. However, the performance of finding flaws was similar in both environments. Participants did not discuss any opportunities for improving the construction plan in either environment. It was also noticed that some participants assumed that the model was relatively accurate, although the experiment aimed to have participants critically review it. This might be related to their limited industry experience, lack of 4D modeling reviews, or lack of clear tasks.

Participants only identified flaws that were related to sequence activities. Only 13 of the 31 participating groups were able to identify sequencing flaws in the construction plan. These primarily focused on two sequencing issues that participants discussed, shown in Figure 9. The left (a) image shows a flaw in the sequence where two steel braces were installed ahead of the supporting members. The other flaw on the right (b) image shows the installation of the second floor before the start of the first-floor grade-beam install. The first flaw was found most frequently. The number of instances when participants found these flaws was similar for both 4DMAR and the screen-based. Seven groups identified at least one sequencing issue using the SB review, while six identified sequencing issues in the 4DMAR. When participants found a flaw in the environment, they usually did not discuss it again in the second environment. Whether there is an advantage to using the 4DMAR or SB cannot be demonstrated, but both can be used to identify flaws. Participants found no missing object flaws or flaws related to the model's construction methods in both environments. This was documented using the notes taken during the experiment when the participants discussed a sequencing issue. The participant sample consisted mainly of students with limited professional experience in construction planning and 4D modeling practices. Most



a) Steel structure sequence.

b) Installation of the second-floor.

Figure 9: Sequencing Issues Found by Participants

had only used 4D authoring tools like Navisworks once or twice before. This lack of deep domain expertise may have caused many to assume the provided 4D model was largely accurate. While the experiment instructions mentioned that 4D models can reveal construction flaws, participants were not explicitly tasked to identify flaws or sequencing errors. Moving forward, we plan to enhance the experiment design by instructing participants to document the observed 4D model flaws or sequencing issues as part of the review exercise.

The 4DMAR has initiated different interactions compared to the screen-based. Figure 10 shows examples of the interaction methods unique to the 4DMAR, such as exploring the model's interior.

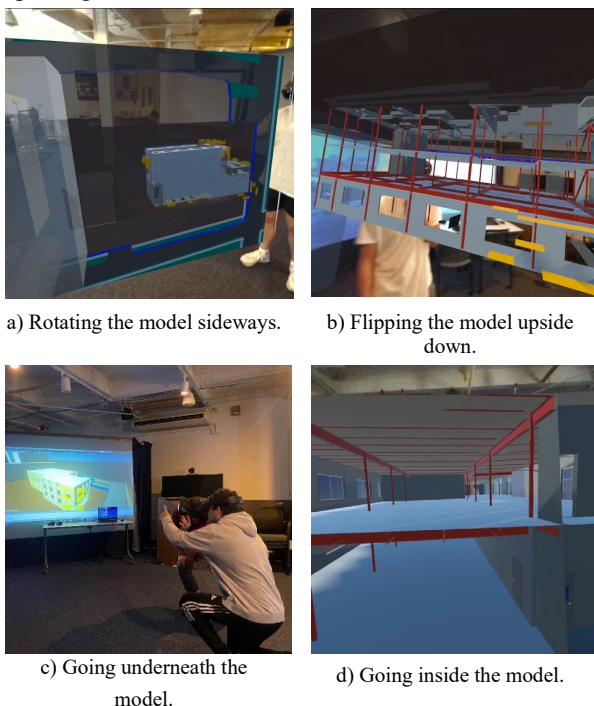


Figure 10 Examples of the Interaction Methods

The primary research question investigated in this study was: Can 4DMAR provide a suitable environment for reviewing 4D construction plans compared to screen-based reviews? As indicated by the questionnaire results in Figure 8, 63% of participants felt AR was better suited for collaborative work and group activities compared to only 18% preferring the screen-based environment, while 19% had no preference. While task performance in identifying construction plan flaws was similar across both environments, the overall user preference for AR's interactive and immersive qualities supports its potential as an engaging platform. By counterbalancing the experiment paths (A and B), an order effect on preferences was not detected based on the collected data. This suggests that familiarity with the AR system did not significantly sway participants' judgments after experiencing both visualization methods.

Conclusions

Planning for construction sequencing is a complicated process that requires careful consideration. Visualizing the construction sequence is beneficial in determining possible challenges and opportunities in a construction plan, which heavily relies on the planners' experience. Collaborative environments that support model interaction and improved or novel visualization have previously shown benefits to the review process.

Participants generally preferred the 4DMAR regarding collaboration activities in the review quasi-experiments. Participants felt comfortable and enjoyed using the AR headsets and felt they could communicate with their teammates. The effect on task performance and collaboration was evaluated using an immersive, multi-user AR to review 4D construction models. Several objectives were achieved in this research. First, a multi-user, collaborative, immersive solution using AR, named 4DMAR, was developed for visualizing a 4D model. An assessment approach was designed and performed to evaluate the performance of the 4DMAR and show its potential to provide a collaborative environment. A comparative study was conducted to measure the performance of 4DMAR. 63% of participants felt AR was better suited for collaborative work and group activities than only 18% preferring the screen-based environment. By counterbalancing the experiment paths (A and B), an order effect on preferences was not detected based on the collected data.

While the results showed a user preference for AR for construction plan review, this has some limitations based on the participant pool and task definition. Future research should examine this technology with industry professionals to critically assess the potential benefits and challenges of adopting AR and address the limited industry experience of the participants to give a better judgment. Another key limitation identified was the low rate of participants detecting sequencing flaws in the 4D construction plan despite this being a primary use case. Incorporating explicit flaw identification tasks will be a critical focus for further developing the 4DMAR system. In addition, complex models that include different building systems should also be used to reflect more complicated challenges within extensive model reviews. Solutions such as performing more systems-selective task reviews to enable more value-based approaches can be explored. However, with the current limited computational power of AR headsets, it is very difficult to visualize large building information models without optimizing the meshes or using other proximity solutions.

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