

MetaModular: A System to Achieve Collaborative Planning Decisions in Modular Construction Projects Using Metaverse Technology

Mohamed Assaf¹, Sena Assaf¹, Yuxuan Zhang², Mohamed Al-Hussein¹, Xinming Li³

¹ Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada

² Department of Management Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China

³ Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada

ABSTRACT: Modular construction has the potential to improve the current state of construction projects. However, its adoption faces challenges due to the need for effective collaboration and coordination among project teams. Tools such as virtual reality have been utilized to address these obstacles. A significant issue affecting existing virtual reality applications for planning modular construction activities is the absence of collaborative virtual environments where geographically remote decision-makers can connect and interact in real-time. This paper develops a MetaModular system by investigating the use of metaverse technology to enhance traditional virtual reality applications, allowing multiple users to communicate within immersive virtual environments. The proposed MetaModular framework includes several min-metaverses (virtual scenes) that encompass all project stages, including manufacturing, transportation, and construction. It offers users numerous virtual features, such as virtual meeting environments, planning parameter predictions, and various means of communication like locomotion, voice chat, and movement synchronization. Unity3D and Photon PUN are used for the multi-user virtual reality model, while AnyLogic develops the prediction and planning model in the virtual environment. The system is implemented in a panelized construction facility to assess its feasibility and effectiveness. Two virtual reality setups are considered to evaluate users' connectivity within the metaverse environment. The results show that 70% to 100% of participants agreed on the system's effectiveness for collaborative and interactive planning and monitoring of modular construction activities. The proposed framework is expected to assist modular construction decision-makers in making informed decisions, improving coordination among various tasks, and proactively identifying potential delays and constructability issues.

1. INTRODUCTION

Modular construction methods have recently experienced significant growth due to their advantages over conventional construction methods, including reductions in schedule and cost. According to reports from the Modular Building Institute, the market share of modular construction has increased from 4.5% in 2020 to nearly 7% in 2023 in North America (MBI 2024). Modular construction alters the typical process of building by shifting most construction work from sites to controlled environments (i.e., factories) (Assaf et al. 2024a). This shift creates a more complex and less flexible supply chain that can disrupt team coordination and lead to decreased productivity and economic viability (Zolghadr et al. 2022). More specifically, it is asserted that stakeholders in modular construction must address multiple planning challenges early in the project, such as transportation constraints and site layout, and should maintain efficient coordination with other project stakeholders. This hypothesis is supported by (Hwang et al. 2018) and (Ezzeddine and García de Soto 2021) who argued that the lack of efficient communication and

coordination among the modular construction teams is one of the most significant adoption challenges. Other challenge types are related to the difficulty of the real-time monitoring of the implementation of modular construction projects. In this regard, Alsakka et al. (2024) mentioned that relying on average rates to track production often shows great deviations from actual production. A similar hypothesis was presented by Dong et al. (2024) who argued that inefficient tracking of assets (for example, precast panels) in modular construction could cause delays and might impact subsequent activities.

In tackling these challenges, numerous solutions were identified in the existing body of knowledge. In particular, digital tools were the main approach followed by researchers. For instance, Ezzeddine and García de Soto (2021) utilized game engine tools to create virtual environments for planning and coordinating various activities in modular construction projects. Their study incorporated numerous virtual scenarios to make a set of planning decisions, including route selection and module installation sequencing. Similarly, Zhang et al. (2023) linked 3D BIM models with game engines to develop virtual environments for proactively planning and coordinating onsite activities in modular construction projects. Another virtual model was also presented by Assaf et al. (2024b), who created game scenes for project planning in MC projects that covered all MC-SC stages. Their study incorporated web features that enabled users to conveniently access these game scenes remotely.

Although the discussed virtual and digital applications hold great potential for modular construction research, creating a collaborative virtual environment for real-time engagement among geographically remote stakeholders remains challenging (Hadavi and Alizadehsalehi 2024). The discussed applications lack a virtual collaboration that is not bounded by space and time constraints, which would enable decision-makers to coordinate, communicate, and visualize different scenarios. Such an environment could facilitate well-informed, consensus-driven decisions while minimizing time, cost, and project disruptions. In this regard and building upon virtual reality technology, the metaverse was introduced as a viable solution for this issue, allowing multiple users to interact and communicate within virtual environments. The metaverse refers to an expansive digital environment that reflects the real world, through which users can interact with each other using virtual avatars (Chen et al. 2024). The applications of the metaverse have been recently widespread in construction research, such as inspection applications (Luleci and Catbas 2024), collaborative design review (Prabhakaran et al. 2022), equipment operations planning (Zhang et al. 2023), and safety (Shi et al. 2019).

The merits provided by the metaverse technologies align in many ways with the discussed challenges in planning and monitoring modular construction projects (Assaf et al. 2024a). For instance, metaverse technologies enable geographically remote users to engage in a virtual environment that replicates the real world, allowing them to discuss, collaborate, and observe the impact of their decisions in various simulated environments and hypothetical scenarios (Luleci and Catbas 2024b). Furthermore, metaverse technologies enable digital twinning to accurately reflect real-time activities occurring onsite or in a factory within the metaverse environment, facilitating efficient tracking and monitoring. To this end, this paper is motivated by the lack of research on the impact of collaborative immersive virtual environments on planning and tracking activities in modular construction projects. The study introduces the MetaModular system, which integrates a metaverse environment into modular construction planning and tracking. It aims to provide modular construction decision-makers with a tool that would help visualize different decisions, assess their impact on a set of KPIs, communicate with other decision-makers, and track real-time updates from sites and factories. The remainder of the paper is organized as follows: Section two discusses the methodology followed in this paper, Section three discusses the MetaModular system development, Section four presents an illustrative case study to discuss the MetaModular system capabilities, and Section five evaluates the MetaModular system.

2. METHODOLOGY

This study adopts the Design Science Research (DSR) method for developing the MetaModular system. DSR is a systematic method for creating artifacts that solve a specific issue and for showcasing the artifact's effectiveness. This process includes four stages: (1) recognizing the problem, (2) setting the objective, (3) creating the artifact, and (4) illustrating the artifact. As discussed in the previous section, many challenges

are inherent in planning and monitoring the modular construction supply chain, including (1) a lack of collaborative virtual environments where graphically remote decision-makers can communicate and interact (Prabhakaran et al. 2022), (2) drawbacks in onsite meetings that are risky, time-consuming, and costly (Luleci and Catbas 2024); (3) lack of integration of various teams in decision-making processes (Ezzeddine and García de Soto 2021); and (4) difficulties in monitoring and tracking of the production (Alsakka et al. 2024) and installation (Dong et al. 2024). The proposed MetaModular framework solves the mentioned challenges through several features: (1) enabling geographically remote stakeholders to connect and communicate in virtual environments in real-time; (2) breaking the time/ space boundaries by providing virtual meetings (mini metaverses); (3) enhancing decisions visualization through immersiveness and allowing users to interact with virtual environments; (4) improving project tracking through real-time data integration; and (5) enhancing accessibility and security through VR authorization log-in features. Fig. 1 maps the capabilities of the MetaModular system with the challenges of modular construction planning and monitoring.

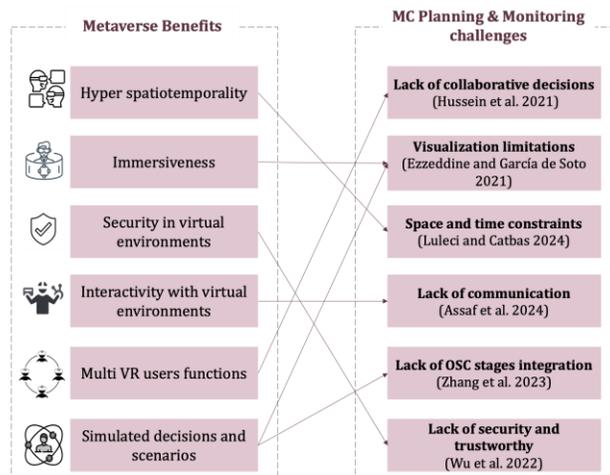


Figure 1: Mapping MetaModular features with the challenges identified in the MC supply chain

Figure 2 offers an overview of the methodology used in this paper. Two primary spaces are involved in developing the MetaModular system: virtual and physical space. In the virtual space, four main components are featured: (1) **virtual avatars**, which represent the users in the virtual environments and are controlled by VR headsets and controllers; (2) **mini metaverses**, which are the virtual scenes (e.g., virtual meeting rooms) within the metaverse environment; (3) **real-time DT model**, which conveys the real-time data input from the site and physical environment to the metaverse environment; (4) **security and connection**, which refer to the security layer for model accessibility (login credentials) and the forms of communication in the metaverse environment (e.g., voice chatting). Conversely, the physical space encompasses the following: (1) **laser scanning**, which entails the precise capturing of a structure's 3D geometry for digitization; (2) **real-time data acquisition**, which involves collecting data from sites and factories to automatically update and trigger specific behaviors within the metaverse environment; (3) **site data**, encompassing all tracking photos and details about the panels (for instance, shop drawings); (4) **real users**, referring to those who will utilize the metaverse technologies (e.g., site, factory, and transportation teams).

To test the MetaModular system, the authors prepared two VR setups, each including the following: 1) a Varjo VR/XR headset, 2) two HTC Vive controllers, 3) two VR bases, and 4) a physical site mock-up. The last item simulates a site condition where users can scan various QR codes to generate data from this site. The scanned data includes three statuses: "Shipped," "Arrived," and "Installed." This information should be accessible to users in the metaverse environment. Participants are also asked to scan a QR code that allows them to take pictures of the physical mock-ups. They can later view these pictures in the MetaModular system when they enter the VR experiment. After the experiment, participants completed a short survey to evaluate the effectiveness of the MetaModular system. The survey questions were selected to test different features of the MetaModular system and aligned with other related VR studies, such as (Luleci and Catbas 2024; Prabhakaran et al. 2022). The survey questions included rating questions (from 1 to 5), opinion questions, and open-ended questions. Table 1 shows the questions asked in the survey.



Figure 2: An overview of the paper's methodology

Table 1: Questions included in evaluating the MetaModular System

Objective	Question
General Information*	<ul style="list-style-type: none"> • Rating of familiarity and experience with virtual reality and metaverse technologies • Rating of familiarity and experience with modular construction planning and monitoring
Virtual environment rating*	<ul style="list-style-type: none"> • (HR1) Sense of physical space in the VR experiment • (HR2) Level of engagement and involvement in the virtual environment • (HR3) Overall comfort and ease within the virtual environment • (HR4) Believability and realism you experienced in the virtual environment • (HR5) Negative effects, such as dizziness, and motion sickness, in the virtual environment
Opinion questions on the MetaModular system**	<ul style="list-style-type: none"> • (HO1) The functionality (planning and monitoring features) of the MetaModular system was appropriate for modular construction planning and monitoring • (HO2) Modular construction stakeholders can use the MetaModular system as a collaborative decision-making environment in planning and monitoring projects. • (HO3) The virtual meeting rooms (i.e., mini metaverses) present a high level of communication among users. • (HO4) The MetaModular system can reduce the safety risks (e.g., hazardous zones) that are included in site (physical) meetings. • (HO5) The level of security in the virtual environment (e.g., login credentials) is appropriate for securing the MetaModular system. • (HO6) The real-time input in the presented model is sufficient to track the installation and transportation updates in modular construction projects. • (HO7) The MetaModular system surpasses conventional virtual meeting methods (such as video conferences) by providing immersive communications, visualized scenarios, and real-time data visualization. • (HO8) Compared to other methods of progress tracking, such as Excel and Google Sheets, the MetaModular system offers a more practical and efficient way to monitor the progress of modular construction projects.
Open-ended questions	<ul style="list-style-type: none"> • Suggestions to improve the MetaModular system

* rating questions are based on a Likert scale (from 1 to 5), **opinion questions were answered according to five choices (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree). (HR) refers to a Hypothesis in the rating section. (HO) refers to a Hypothesis in the opinion section.

3. METAMODULAR SYSTEM DEVELOPMENT

This section discusses the specifics of MetaModular system development. The MetaModular includes an extensible and cross-platform server that enables users of modular construction in different geographical locations to connect and communicate in virtual environments. The Unity3D game engine tool serves as the primary developing tool in this research. It is also used as the hub where several tools, plugins, and models are integrated, including the following: 1) BIM models, 2) Photon Unity Networking, 3) Mapbox, 4) AnyLogic Cloud, 5) JSON libraries (real-time data), 6) Photon Voice library, and 7) VR login functions. Each of these has a function that plays a role in the MetaModular system. Starting with the **BIM models**, FBX files are exported from the Autodesk Revit tool to the Unity3D tool to be used on the onsite virtual scenes. Other BIM models were created through laser scanning and point clouds. These models are for existing facilities (such as the offsite factories), which are part of the virtual meeting rooms in the MetaModular system. The **Photon Unity Networking** is used to create the multi-user VR experience. It establishes a remote connection that allows users' transforms and movements to be synchronized over the network by triggering remote procedure calls (RPCs). **Mapbox** is used to create 3D maps of project locations. It is imported into Unity3D, and the coordinates (longitude and latitude) of each project are indicated to automatically build a 3D map of that location. This tool directly serves the logistics team to visualize different routes and make informative decisions within the Metaverse environment. In order to have quantitative collaborative planning, the **AnyLogic cloud** tool is employed within the Metaverse environment. It is built on discrete event and agent-based simulation tools to explore various decisions that influence different KPIs (e.g., manufacturing and installation times). Moreover, to incorporate real-time data from sites and manufacturing plants into the Metaverse environment, **JSON libraries** are utilized with the Unity3D tool. These libraries retrieve data (e.g., images from sites, wall panel statuses, and current progress) from Google Cloud and input it into the C# scripts of the Unity3D tool for the end-user to visualize and interact with. The **Photon Voice library** is used to allow VR users to communicate via a voice chat function established over the network. Finally, to ensure network security and reliability, the virtual environments are supported with **VR login credentials** functions to only allow authorized users to enter the Metaverse environment. The developed Metaverse environment is built into an executable file (.exe) and provided to the projects' stakeholders.

By integrating all the mentioned tools and plugins, various virtual scenes (mini metaverses) are created, including the following: (1) Login scene: In this scene, the user specifies their name tag and enters the network password that is shared with them. They can then click the "Connect to Metaverse" button to join the network; (2) Home (Tutorial) scene: after the user joins the network, they can familiarize themselves with navigation controls, such as locomotion movement, rotation, and teleportation movement, and other UI interaction, such as avatar customization and buttons selection. They can also view the available mini metaverses, including factory plants and project sites; (3) Factory plant scenes: if the user clicks on one of the factory UIs in the Home scene, they can enter a mini metaverse of the plant. This mini metaverse is created through the laser scanning and point cloud methods discussed in the methodology section. Here, users can communicate and explore details about the panels (for example, blueprints and shop drawings). They can also access the planning model, allowing them to examine the impact of their decisions on a set of KPIs (e.g., project completion time); (4) Site scenes: in the Home scene, users can select a project that interests them. Once inside a site scene, they can monitor the progress of the wall panels, such as whether they have been shipped from the factory, arrived on-site, or been installed. Additionally, users can view progress photos from sites within the Metaverse environment.

4. ILLUSTRATIVE APPLICATION OF THE METAMODULAR SYSTEM

Illustrating the artifact is a crucial component of the DSR research method. This section examines a case study used to implement the MetaModular system. A case study of wall and floor production lines located in Edmonton, Canada, is presented to showcase the capabilities of the MetaModular system. Figure 3 displays the point clouds scanned from both the wall and floor plants. These virtual scenes are then imported into the Unity3D tool as part of the Metaverse environment. In this illustrative application, the details of ten offsite construction projects are taken from Wei et al. (2024). Each of these projects is included

as a mini metaverse in the MetaModular system, allowing users to select any of these projects and engage with other geographically remote users for planning and tracking purposes. Figure 4 shows some of the MetaModular customization features that are offered to VR users. Part A shows a VR user logging into the Metaverse environment with their username and password, and Part B shows a user selecting an avatar to represent them in the Metaverse. It should be noted user representation (i.e., avatars and name tags) in metaverses significantly impacts the user experience and greatly influences user interactions in collaborative virtual environments (Pan and Steed 2017). Figure 5 shows a sample of the interaction features provided to users in the MetaModular system. Part A shows two users interacting with shop drawings of different wall panels in the factory. This feature is equipped with grabbing control, where the user in the metaverse can grab the drawing of their interest and discuss it with other users. The user can access the project that they desire by interacting with the UI, as shown in part B. Part C shows users observing real-time changes in the status of the wall panels based on established criteria (for example, the site supervisor scanning QR codes for specific panels to be installed or arrived on site). Part D shows users interacting with the planning model in the metaverse. Through this feature, users can enter a set of decision variables and observe their effect on various KPIs while having immersive communication.

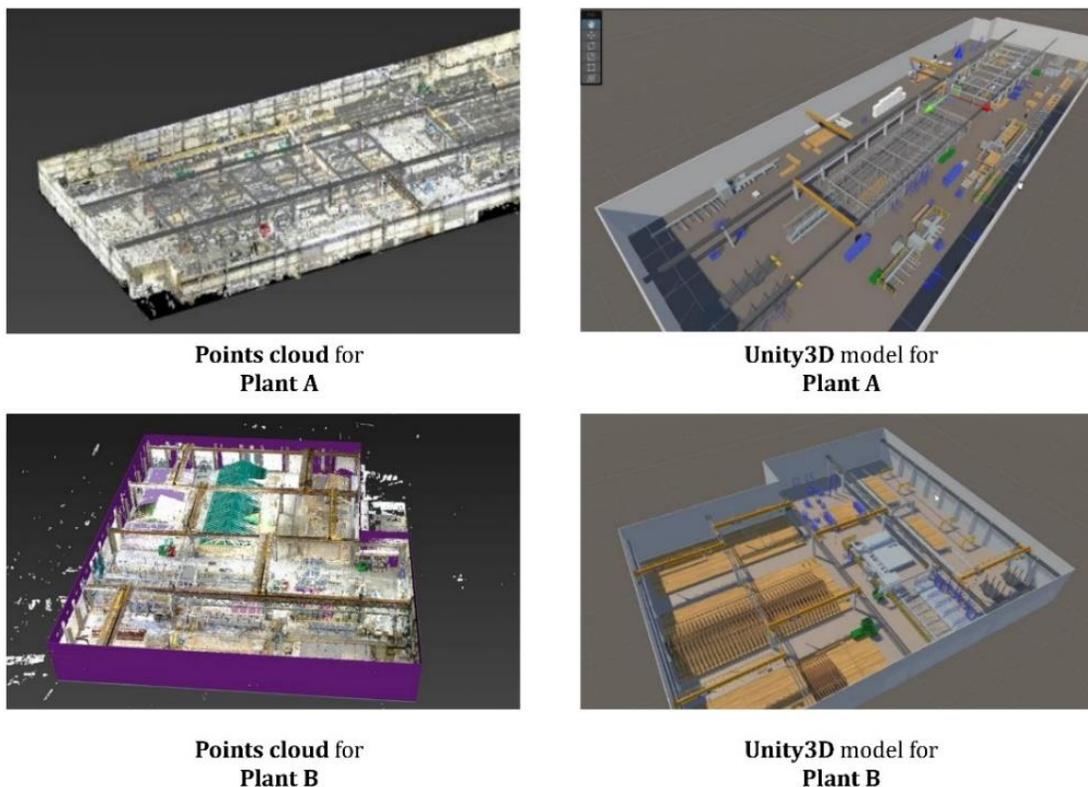


Figure 3: Point clouds of plants and their conversion to Unity models

5. EVALUATION OF THE METAMODULAR SYSTEM

Overall, ten participants took part in the study across five separate experiments. Each experiment involved two participants who entered the same metaverse simultaneously. The total duration of each experiment ranged from 20 to 30 minutes, encompassing all the scenes discussed in the previous sections. Participants tested various functions in the metaverse, including communication with other VR users, interactions with the virtual environment, and observation of real-time data from different modular construction sites. Furthermore, participants were asked to engage with a planning and predictive model and observe changes in various KPIs, such as project performance, manufacturing time, and waiting time. After the experiment, users were requested to complete a short evaluation survey to assess the system's usability and efficiency. Questions included in this survey are displayed in Table 1.

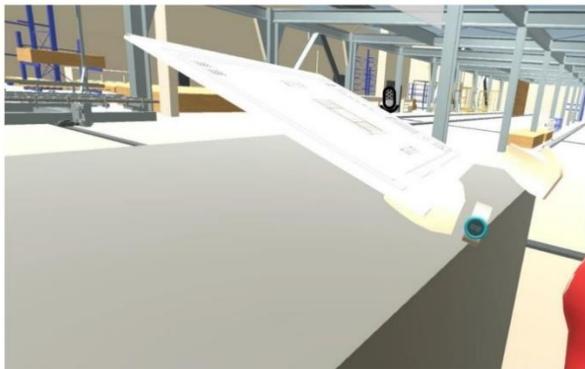


a) Entering user's name tag



b) Avatar Customization

Figure 4: User identification in the MetaModular system



a) Two users discussing a shop drawing



b) A user selecting a project mini metaverse



c) Users observing real-time site updates



d) Two users interacting with the planning model

Figure 5: Multi-VR users' interaction with the virtual environment

As can be deduced from Table 1, questions (HR1 to HR5) mainly focused on assessing the virtual environment itself. As Figure 6 shows, for questions (HR1 to HR4), 80%, 90%, 80%, and 80% of the answers rated the score of four or above, indicating that the metaverse environment has a sound sense of presence, high level of engagement, comfortable, and has a high level of realism. However, 20% also expressed that they experienced some dizziness and motion sickness in question HR5. This aligns with the findings of Prabhakaran et al. (2022), who recommended that extreme care should be considered during

the VR experiments to mitigate possible negative effects. On the other hand, questions (HO1 to HO8) primarily focus on evaluating the effectiveness of the MetaModular system as a viable solution to address modular construction planning and monitoring challenges. In this regard, Figure 7 shows that 90%, 100%, and 70% agree with the hypotheses included in questions (HO1 to HO3), indicating that the presented metaverse environment can provide a collaborative platform with a high level of virtual communication. In question HO4, all participants indicated that the MetaModular system is a viable solution to enhance the safety of the onsite meetings by shifting it to the metaverse environment.

As security is an essential part of the metaverse technology, users were also asked in question HO5 about the level of data security in the shared virtual environment. All participants (100%) reported that the presented VR login with credentials method is appropriate enough to secure the metaverse environment. Questions (HO6 to HO8) evaluated the real-time input in the metaverse, as well as comparing it with other methods. 80% of the answers indicated that the real-time data input in the metaverse environment is adequate to track wall panels in the presented statuses (e.g., *Shipped*, *Arrived*, and *Installed*). Additionally, 90% of the answers indicated that the MetaModular system provides a more practical method than conventional video conferences by facilitating immersive experiences, real-time data, visualized scenarios, interaction with virtual environments, and virtual planning. Furthermore, 80% of the answers indicated that relating real-time data to the 3D elements in the virtual environment is a better way to track projects compared to conventional databases and cloud sheets (e.g., Google Sheets). The last question was an open-ended question where participants shared ideas about how to improve the current MetaModular system, including the following: (1) improving grabbing control in the virtual scenes, (2) adding a feature to allow metaverse users to take notes and share them other platforms outside the metaverse, (3) improving the quality of the shop drawings (e.g., enlarging text) so that it is clearer for the metaverse users, (4) allowing users to enable and disable the communication channels (e.g., voice chat) in the metaverse environment.

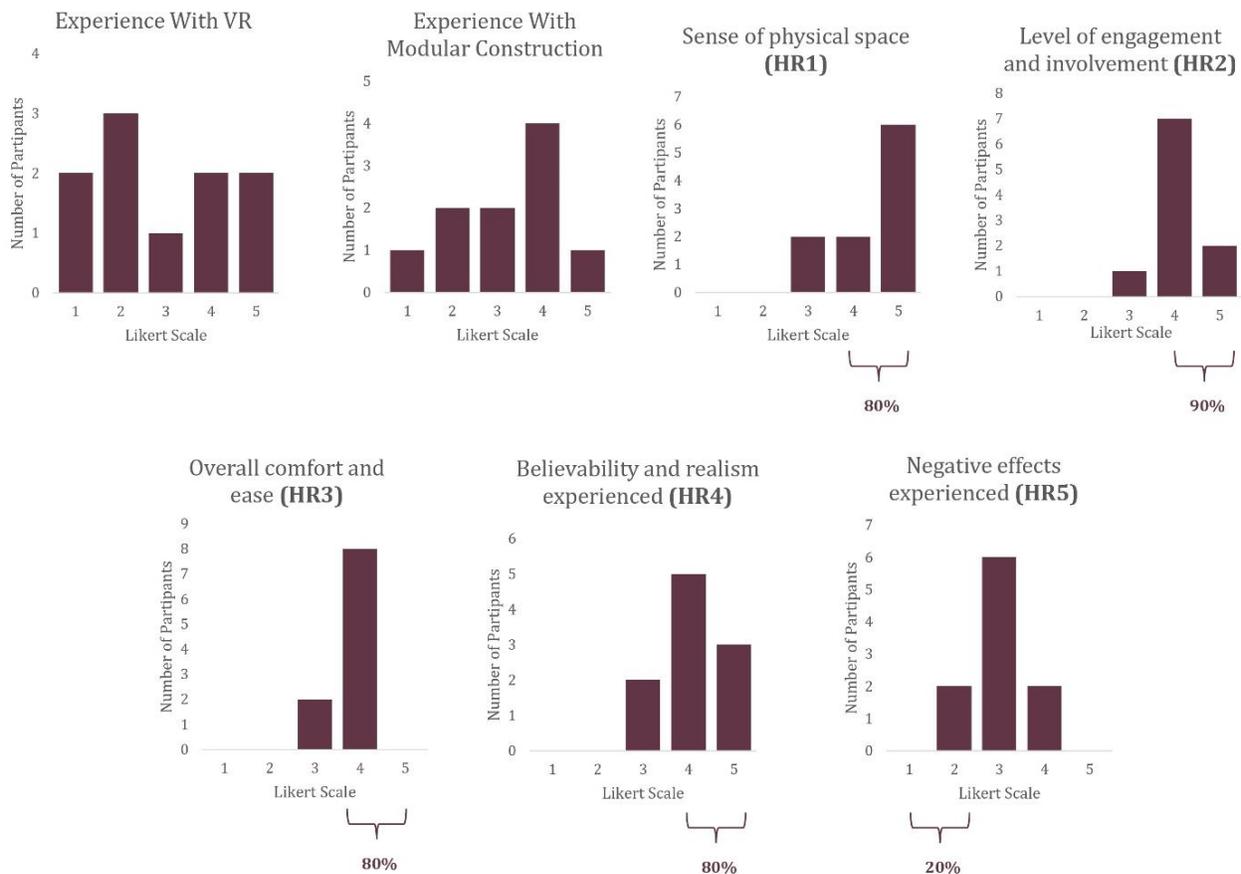


Figure 6: Rating of the VR experience in the MetaModular

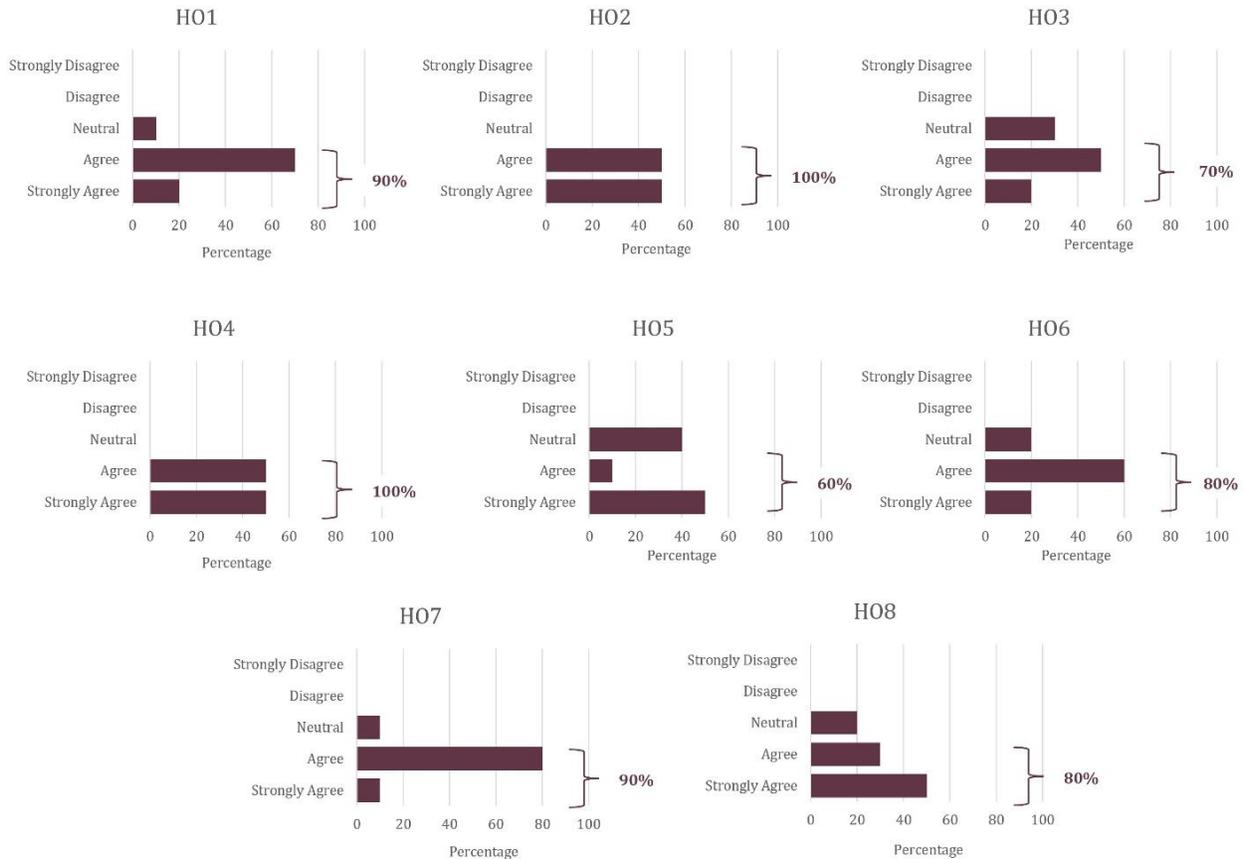


Figure 7: Evaluating the efficiency of the MetaModular system

6. CONCLUSIONS

This research introduces the MetaModular system, designed to apply the metaverse technology to improve collaboration and communication among modular construction decision-makers during planning and monitoring activities. The MetaModular system was developed based on the DSR method and includes virtual communication, real-time updates, interaction with the virtual environment, and virtual planning models. A case study of a panelized construction company is introduced as an illustrative example of the MetaModular system. The MetaModular system incorporates several mini metaverses, including factory plants mini metaverses and various project mini metaverses. To evaluate the MetaModular system, two VR setups were prepared for the multi-VR user experiments. The MetaModular system was evaluated in five distinct VR experiments involving ten participants. The results indicate that the MetaModular system effectively supports coordination, planning, and tracking activities, with 70% to 100% of participants reporting agreement with the established hypotheses (HO1 to HO8). Future studies will focus on targeting a larger sample to test the MetaModular system. Furthermore, statistical tests and sensitivity analysis will be applied to further assess the usability and effectiveness of the MetaModular system. Additionally, the real-time data about wall manufacturing will be integrated into the plant mini-metaverse to enhance project monitoring.

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