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INTEGRATION OF 4D BIM AND VR FOR INTERACTIVE MODULAR BUILDING MANUFACTURING SIMULATIONS IN A FACTORY-CONTROLLED ENVIRONMENT

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Abstract

The manufacturing of modular buildings in factory-controlled environments is complex process, involving intricate task sequencing, resource allocation, and rigorous quality control. Traditional visualization and scheduling methods frequently fail to communicate these complexities effectively, resulting in inefficiencies, scheduling errors, and cost overruns. This research addresses these challenges by integrating Building Information Modelling (BIM) and Virtual Reality (VR) into a unified, interactive 4D simulation environment to enhance user comprehension, enable real-time interaction, and optimize modular construction workflows. A comprehensive 4D BIMVR system is developed that synchronizes detailed 3D BIM models with time-based scheduling data, creating an immersive environment for interactive visualization and dynamic task management. The system was evaluated through user testing in a modular building manufacturing setting, with participants completing a survey to provide feedback on their VR experience. Survey results showed high satisfaction with visual realism, metadata accessibility, and workflow clarity. Users noted that the immersive environment improved their understanding of complex sequences, enabled earlier detection of scheduling conflicts, and enhanced overall planning efficiency, demonstrating the system's potential to optimize modular construction processes. The primary contribution of this research is the advancement of modular construction methodologies through immersive digital technologies, establishing a robust foundation for future innovation in digital construction practices.

Keywords: 4D BIM, modular building manufacturing, user testing, VR.

1. Introduction and background

Modular construction has emerged as a transformative approach in the construction industry, offering significant advantages over traditional building methods including reduced time-to-completion, improved quality control, cost efficiency, and enhanced sustainability [1]. This method involves the assembly of pre-manufactured components or modules in a controlled factory setting, which are subsequently transported to the construction site for final assembly. The controlled factory environment of modular construction, while providing advantages in quality and efficiency, introduces significant production management challenges [2] which includes the coordination of module manufacturing processes, optimization of factory layouts, management of material flows, and alignment of production schedules with transportation and on-site assembly requirements [3]. These complexities often result in inefficiencies, scheduling conflicts, and quality control issues that impact project delivery and stakeholder satisfaction. Logistics remains one of the most significant challenges, particularly regarding transportation limitations and module size constraints. Brookfield and Cooke stated that a critical factor in any modular project is determining the maximum module size that can be fabricated, shipped, and transported. For onshore projects, modules can reach up to 5,000 tons, although the actual feasible size and weight depend on factors such as transport routes and the availability of suitable equipment. Sequencing challenges in modular construction relate to workflow scheduling and production line efficiency. Keyes argues that factory-built homes need greater consistency in design to make production and installation more efficient, noting that as soon as you start changing things you have another variable to consider.

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BIM has revolutionized construction project management by enabling detailed 3D digital representation of buildings and comprehensive information management throughout the project lifecycle [4]. BIM enables project stakeholders to see and adjust the entire timeline of a construction project, making it essential for planning, predicting, and preventing potential bottlenecks. In the context of modular construction, BIM applications have been implemented to enhance various aspects of the process. Lee and Kim developed a BIM-based 4D framework capable of managing processes, resources, and quality based on factors related to the module manufacturing environment [5]. This framework leverages the advantages of 4D simulation to provide more precise information than conventional documents, helping manufacturers plan the manufacturing process in detail and access information about material quantities for each process. Darko et al. identified critical applications of BIM in modular integrated construction risk management, including productivity improvement of precast shop drawings, logistics planning through BIM-GIS integration, and parametric modelling for designing offsite construction [6]. These applications demonstrate BIM's potential to address various challenges throughout the modular construction process.

VR technology has proven highly effective in construction by enhancing spatial understanding, training, and decision-making through immersive, interactive experiences, especially where real-life conditions are inaccessible [7]. It facilitates visualization of construction sequencing and offers a flexible learning environment, eliminating the need for scheduled site visits and reducing exposure to on-site hazards [8]. Research indicates that VR users outperform those using desktop-based methods by 21.86%–142.92% in design review and planning tasks, underscoring its capacity to improve performance and comprehension in construction workflows [9]. Applications of VR span various domains, including safety training, architectural design reviews, and 4D-based constructability analysis. For instance, Jin and Nakayama integrated virtual 3D safety exercises into engineering programs to enhance laboratory safety awareness, while Zhao and Lucas utilized VR simulations for electrical hazard training [7]. In modular construction specifically, VR applications have been limited despite their potential benefits. Ghimire et al. applied a 4D schedule with immersive VR on a modular project assembly and found that most participants who experienced the 4D BIM schedule with immersive VR strongly agreed it was an easy and straightforward way to visualize the project, understand the schedule, and find errors [10]. The research concluded that implementing a 4D BIM schedule with VR technology can enhance the fabrication and assembly performance of modules.

The integration of BIM and VR represents a promising approach to address visualization and workflow challenges in construction. BIM combined with VR enables architects to visualize and manipulate building models in an immersive 3D environment, facilitating greater design accuracy and better understanding of projects [9]. This integration significantly improves the efficiency of teamwork, as project participants can overcome the limitations of paper drawings or 2D models that often transmit error messages. Various integration approaches have been developed with increasing sophistication. Boton explored the use of VR for 4D-based collaborative constructability analysis and review through a comprehensive, structured framework [11]. This approach enables stakeholders to visualize and adjust project timelines in previously unimaginable ways. Salem et al. identified that BIMVR integration can benefit all phases of construction projects, including planning, design, construction, and asset management [12]. The integration facilitates virtual walkthrough, schedule visualization, clash detection, and as-built modelling, enhancing decision-making and coordination throughout the project lifecycle. Recent research has demonstrated BIM-VR integration's potential to enhance construction management by improving transparency and precision in project management, helping managers better control construction progress and costs, and reducing rework [13]. Despite these advantages, challenges remain in data compatibility, requiring further research to develop more seamless integration between physical construction sites and virtual models [13]. The literature review reveals that while both BIM and VR have been applied separately in construction contexts with positive outcomes, their integration specifically for modular construction optimization remains limited. The significant benefits demonstrated in isolated applications suggest that a unified 4D BIMVR system could substantially enhance modular construction workflows by addressing the fundamental challenges of visualization, sequencing, and coordination specifically in a factory-controlled environment. This research aims to address this gap by developing and validating such an integrated system in a practical modular factory-controlled environment.

This research addresses the visualization and scheduling challenges in modular construction by developing an integrated 4D BIMVR system that combines detailed 3D models with scheduling information in an immersive virtual environment. The integration aims to enhance stakeholder understanding of complex construction sequences, enable real-time interaction with digital models, and optimize modular production workflows. Through this approach, the research seeks to address the limitations of traditional visualization and scheduling methods that frequently fail to communicate the complexities of modular construction effectively.

2. Methodology

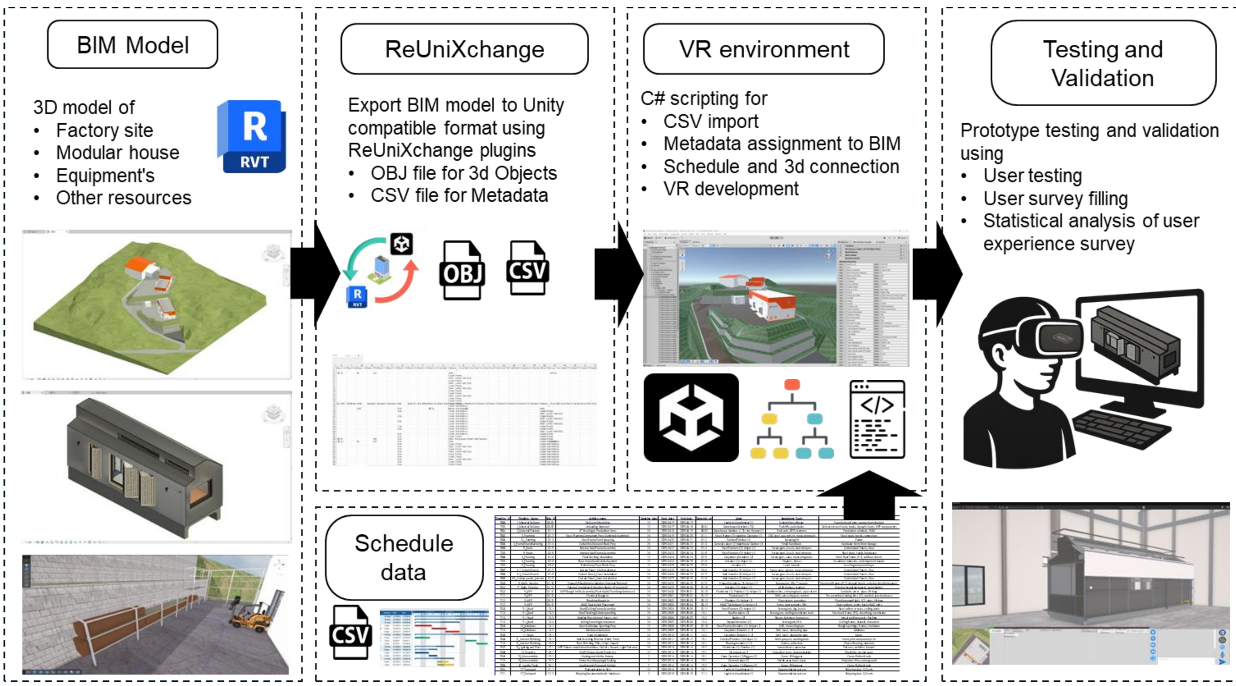

Fig.1. Research methodology

Fig. 1 illustrates the comprehensive methodological framework employed in this research, which initiates with the development of detailed BIM using Autodesk Revit for a modular construction factory, residential modules, and associated equipment. These BIM models, encompassing both geometric and semantic data, were exported using the custom-built ReUniXchange plugin. The export process yielded high-fidelity OBJ mesh files for geometric representation and a metadata-rich CSV file containing element identifiers, categories, built-in properties, and user-defined parameters. Within Unity, the CSV data were programmatically parsed using C# scripts, which mapped metadata to the corresponding GameObject through Scriptable Objects, establishing bidirectional links for interactive element-level queries. Additionally, a construction schedule stored in a second CSV was integrated and mapped to the BIM components. This enabled a behavior tree-based control system to manage object visibility, activation states, and animated transitions according to the defined task timelines, thereby enabling an interactive 4D simulation experience. The fully integrated scene was deployed for OpenXR-compatible head-mounted displays, facilitating an immersive VR environment in which users could explore the modular factory virtual twin, examine element properties, and initiate construction phase transitions. The system was evaluated by seven users from the architecture, engineering, and construction (AEC) domain, who performed structured tasks related to information retrieval and schedule control. Post-experience feedback was collected through a Likert-scale survey assessing perceived usability, usefulness, and spatial understanding. The survey responses demonstrated strong internal consistency, and descriptive statistics were used to assess the system's potential for adoption in real-world modular construction workflows.

3. BIMVR system prototype

The development of the BIMVR prototype system followed a structured workflow focused on importing semantically enriched BIM data, animating construction sequences, and designing interactive user interfaces to support immersive engagement. The implementation was carried out within the Unity 3D development environment, utilizing both built-in and custom-developed components to address the specific requirements of modular construction simulation. The subsequent section will explain in detail how each step is carried out to create BIMVR System.

3.1. BIM model development and exchange

The BIM model development process served as the foundational stage for the BIMVR system. It involved creating detailed Building Information Models using Autodesk Revit to represent both the modular housing unit and the factory environment in which the assembly and production take place. As shown in Fig. 3, the modular house is designed as a single prefabricated unit, capturing both architectural and structural elements, including interior layouts, façade components, and embedded systems such as kitchen and bathroom fittings. In addition to the module, a comprehensive BIM model was developed for the entire factory site. This included spatial zoning for various stages of modular construction, such as material delivery, structural framing, MEP installations, and quality control areas. To ensure realism and completeness, supplementary 3D models representing supporting materials and construction equipment, such as Forklift, overhead crane, trailers etc., were also developed and aligned with the spatial configuration of the factory.

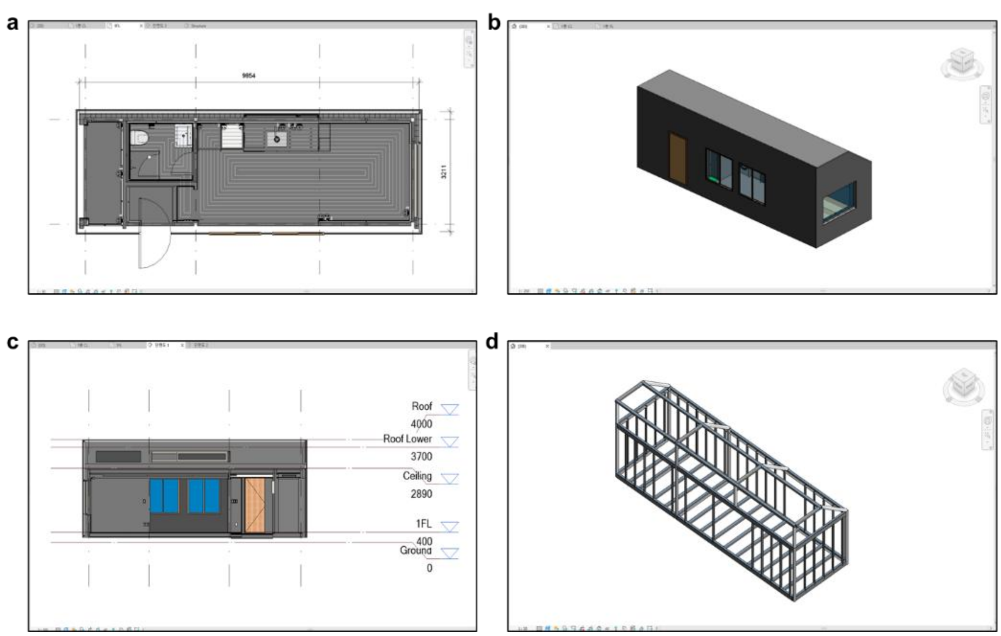

Fig. 2. Single module house BIM model to be manufactured in a factory

Modular units, factory layouts, and equipment were exported as OBJ meshes to preserve geometric fidelity, while accompanying CSV files captured semantic attributes such as element IDs, categories, and custom metadata. Within Unity, custom C# scripts were developed to parse and instantiate this data. Each 3D model was mapped to its corresponding metadata, enabling accurate reconstruction of the virtual environment with semantic depth.

3.2. BIM simulation and VR integration

To simulate the modular construction process, a timeline-based animation system was implemented. Construction schedule data was structured in CSV format, defining the sequential appearance and behavior of BIM components. The CSV dataset provides a detailed breakdown of a modular manufacturing workflow, including activities from material scheduling and framing to final transportation and handover. It documents sequential tasks with their durations, start and end dates, and dependency relationships to ensure logical project progression. Alongside scheduling information, the dataset captures labor assignments, necessary equipment and tools, and associated 3D material components for each task, reflecting a comprehensive view of resource planning. Unity's playable director and timeline components were employed to animate the visibility, position, and material state of each element according to its assigned phase. Additional scripting logic was used to dynamically control the animation flow, including the ability to pause, replay, or jump between phases. This system allows users to observe the factory processes unfold over time, closely reflecting real-world production workflows. Fig. 3 shows different stages of the simulation in the VR environment.

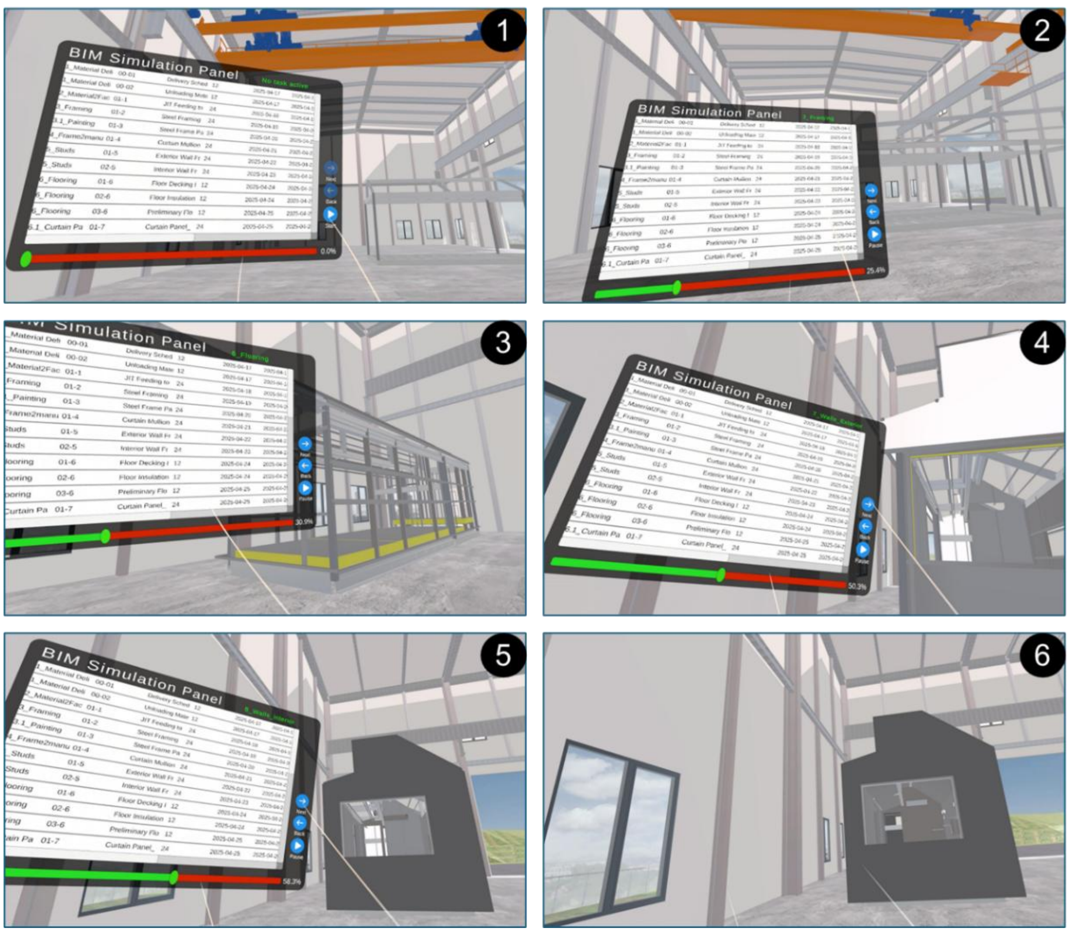

Fig. 3. BIM simulation in VR for single module house

A customized user interface (UI) was developed to facilitate intuitive interaction and simulation control. Built using Unity's UI Toolkit and integrated with the XR Interaction Toolkit, the interface includes features such as a phase navigation panel, schedule data display windows, active task in the manufacturing process, the progress of the manufacturing in percentage and bar, and simulation control buttons (play, pause, next, previous). For VR users, the UI was adapted to a floating panel format, accessible through controller input and designed for minimal occlusion during exploration. The UI also includes tooltips and highlight features to guide users through different components and construction stages.

The system supports both desktop and immersive VR modes. In desktop mode, users navigate using standard first-person controls, while in VR, users interact through teleportation, ray casting, and grab interactions provided by Unity's XR Interaction Toolkit. Interaction logic was extended to include metadata inspection by pointing at BIM components, which triggers contextual information panels displaying relevant semantic attributes. This promotes a deeper understanding of the construction logic and component interdependencies. The BIMVR prototype was developed with scalability in mind. The modular code architecture allows easy replacement or extension of core components such as data loaders, timeline interpreters, or interaction handlers.

4. Testing and validation

To obtain formative feedback on the BIMVR prototype, a pilot usability study was conducted with a small but heterogeneous group of participants (n = 7). The sample comprised graduate students with limited VR exposure. Each participant completed a 15-minute protocol in a controlled laboratory setting using a Meta Quest 2 HMD and standard VR controllers. After a brief acclimation period, participants were asked to: (1) navigate freely through the virtual factory, (2) inspect metadata panels of simulation, and (3) play, pause, and scrub the construction-sequence timeline. Verbal think-aloud comments were encouraged but not recorded for quantitative analysis. Immediately afterwards, testers filled out the bilingual survey described, which comprised eight 5-point Likert items and four categorical check-box questions that minimize open-text burden while still capturing areas for improvement. Responses were collated in a spreadsheet and imported into Python for analysis.

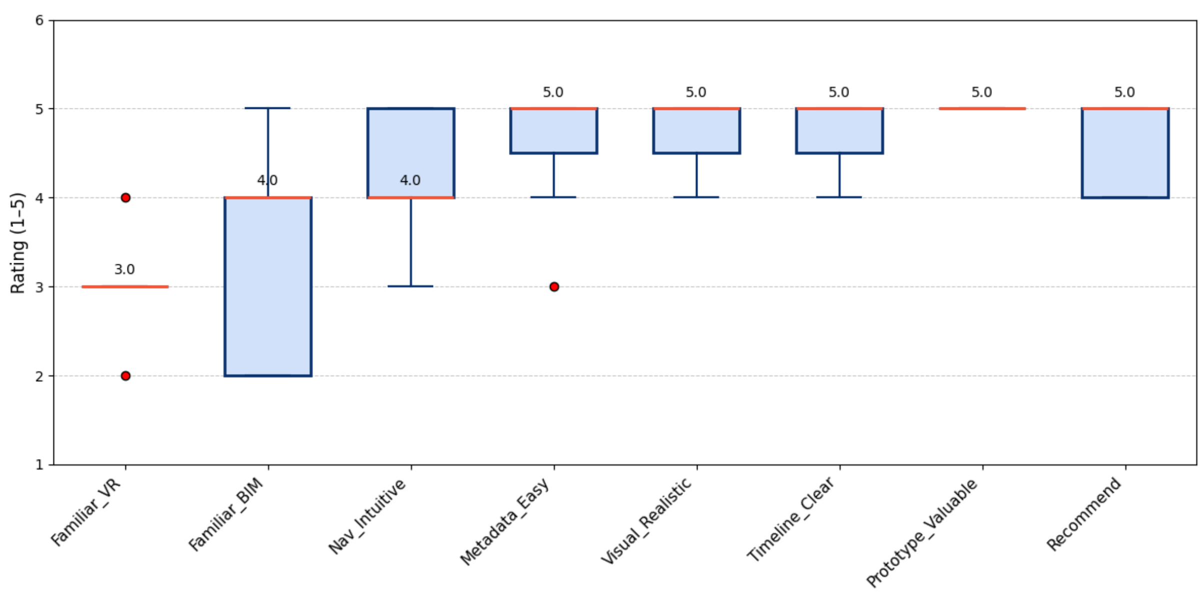

Fig. 4. Box plot for the user rating based on the simulation experience in VR

Fig. 4 shows distribution of participant ratings across eight usability and utility metrics, with box plots showing the median (red line), (IQR) interquartile range (shaded box), whiskers (±1.5 × IQR) and outliers (red dots). In terms of prior familiarity with VR (Familiar_VR), responses were widely dispersed: the median score was 3, but both low (2) and relatively high (4) outliers fell outside the narrow interquartile range (IQR = 0), indicating heterogeneous VR experience among participants. By contrast, familiarity with BIM

(Familiar_BIM) showed a broader central tendency (median = 4, IQR = 2-4) and an extended range (min = 2, max = 5), reflecting moderate variation in domain knowledge.

Ratings of navigation intuitiveness (Nav_Intuitive) also exhibited moderate spread (median = 4, IQR = 4-5), suggesting that most users found the interface reasonably straightforward. Perceptions of metadata accessibility (Metadata_Easy) and timeline clarity (Timeline_Clear) were strongly positive: both yielded a median of 5 and narrow IQRs (4.5-5), with whiskers spanning no lower than 3 and 4, respectively. Similarly, visual realism (Visual_Realistic) attained a median of 5 (IQR = 4.5-5), indicating consistent agreement on the fidelity of the immersive environment. Notably, prototype valuability (Prototype_Valuable) was unanimously rated at the highest possible score (median = 5, IQR = 5-5), demonstrating unequivocal endorsement of the system's utility for modular-construction simulation. Finally, recommendation likelihood (Recommend) showed a strong positive skew (median = 5, IQR = 4-5), with most participants indicating they would advise colleagues to use the platform. Overall, these results suggest that while user experience and interface clarity were highly rated, variability in prior VR and BIM familiarity may warrant targeted onboarding to ensure equitable effectiveness across all users.

In Fig. 5a, participants most frequently identified smooth locomotion as problematic, with three separate mentions highlighting difficulties in achieving fluid movement within the VR environment. In contrast, object selection, UI button placement, and teleportation each received only a single mention, suggesting that while these aspects were noted as confusing by some users, they were less pervasive than the locomotion issue. The comparatively low frequency of comments on object selection and UI layout indicates that core interaction affordances were generally acceptable, but that the overall movement paradigm requires refinement to improve user comfort and spatial orientation. As shown in Fig. 5b, AI-driven schedule optimization emerged as the most requested enhancement, reflecting user interest in automated sequencing and decision-support to complement the manual timeline controls. Multi-user collaboration and real-time BIM synchronization followed closely, underscoring a desire for shared, concurrently updated workflows. Less frequently cited but nonetheless notable were requests for enhanced graphics, and voice control, indicating that users value improvements in visual fidelity and hands-free interaction, albeit secondary to collaborative and intelligent-automation features. Together, these findings prioritize future development efforts toward robust AI scheduling, synchronous multi-user support, and live BIM data integration.

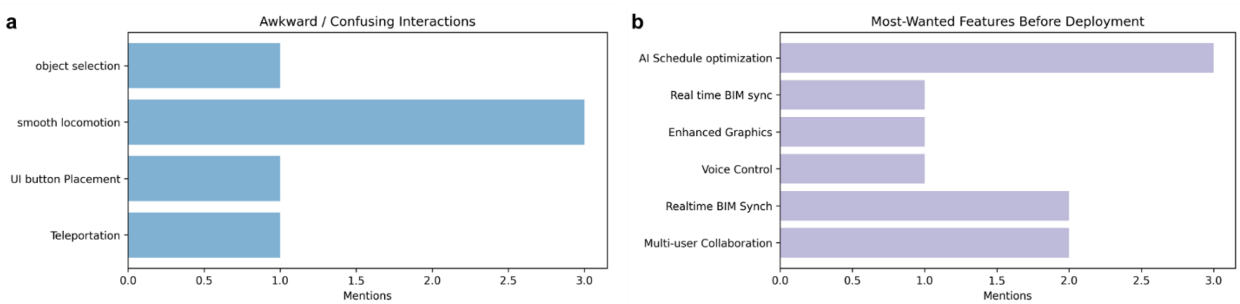

Fig. 5. (a) Distribution of mentions for "awkward or confusing" interaction modalities, (b) Distribution of most-wanted features before final version deployment

Finally, the uniformly high ratings for the prototype's perceived value in training scenarios underscore the utility of continuing development. Even with fewer than ten evaluators, the mixed-methods survey and targeted visual analytics have provided a clear roadmap for the subsequent design iteration while maintaining methodological rigor appropriate to an exploratory pilot.

5. Conclusion

Modular construction in factory-controlled environments offers significant advantages in quality, speed, and sustainability, yet managing the complex sequencing of tasks and resource allocation remains a persistent challenge. Traditional scheduling and visualization methods often fail to effectively communicate production workflows, leading to inefficiencies and errors. To address these issues, this study developed an integrated 4D BIMVR system that combines semantically enriched BIM models with detailed time-based scheduling data within an immersive VR environment. A modular building manufacturing scenario was modelled, and the system was validated through user testing and structured surveys. The evaluation revealed high user satisfaction with the system's visual realism, metadata accessibility, and construction sequencing clarity. Participants reported that the immersive experience enhanced their understanding of production workflows, enabled early detection of potential scheduling conflicts, and improved planning efficiency compared to conventional tools. Overall, the findings confirm that integrating 4D BIM and VR technologies significantly strengthens modular manufacturing management by improving visualization, stakeholder engagement, and proactive decision-making.

The primary contribution of this study lies in the design, development, and validation of a fully integrated 4D BIMVR platform specifically tailored for modular building manufacturing within a factory-controlled environment. Unlike traditional 4D simulations that primarily offer passive timeline visualizations, this system introduces interactive control over construction sequences, real-time access to semantically enriched BIM metadata, and immersive navigation through a digital twin of the factory environment. This contribution bridges a critical gap between theoretical 4D BIM models and practical, immersive manufacturing management tools, providing a robust foundation for future innovation in digital construction technologies for industrialized building methods.

Besides the benefits and contributions, the study has several limitations, including manufacturing simulation for single module in a factory rather than multiple manufacturing process taking place at the same time, a small sample size of user testing and validation, and testing within a controlled laboratory environment rather than a live factory floor. Future work will focus on scaling the system for multiple manufacturing process in the same factory environment, larger user cohorts, integrating real-time BIM synchronization, voice control within the immersive environment, artificial intelligence based conversational agent, enhanced multi-user collaboration capabilities, and embedding AI-driven scheduling optimization to further automate and refine modular production planning.

Acknowledgements

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