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A Quality Management Method for Prefabricated Building Design Based on BIM and VR-Integrated Technology

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Abstract: Quality management in the design phase is crucial for determining the overall quality of prefabricated buildings. However, traditional design methods can no longer meet the complex design, component, and nodal requirements of prefabricated buildings. This study proposes a quality management framework for the prefabricated building design phase based on building information modeling (BIM) and virtual reality (VR) technologies to enhance design precision and satisfaction. Applying this framework to a prefabricated building project in Shenzhen, China, it was found that compared to traditional 2D drawing methods, the design issues feedback during drawing reviews decreased by 41.35%. Compared to solely using BIM technology, the number of design collisions identified through collision detection increased by 28.35%, and feedback on design issues during drawing reviews decreased by 15%. Furthermore, the framework was tested to prove its usability, effectiveness, and functionality. The framework, integrating the rich architectural information of BIM with the immersive experience of VR, contributes to focusing on the design process, improving design tools, optimizing design workflows, significantly reducing design errors, and enhancing the quality of prefabricated buildings.

Keywords: prefabricated building; design quality; building information modeling; virtual reality

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Citation: Zhou, M.; Wang, J.; Yu, B.; Chen, K. A Quality Management Method for Prefabricated Building Design Based on BIM and VR-Integrated Technology. *Appl. Sci.* **2024**, *14*, 1635. https://doi.org/10.3390/app14041635

Academic Editor: Oscar Galao

Received: 17 December 2023
Revised: 4 February 2024
Accepted: 7 February 2024
Published: 18 February 2024

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1. Introduction

Prefabricated building refers to the process where parts or all components of a building are prefabricated in a factory and then transported to the construction site, where they are assembled into a building using reliable connection methods [1]. Compared to traditional construction methods, prefabricated buildings feature standardized design, industrialized production, mechanized construction, and informational development [2], which helps with promoting energy saving and emission reduction [3], improving project quality [4], and reducing construction periods [5].

The development of prefabricated buildings demonstrates trends of globalization, technology-driven processes, and environmental friendliness. An efficient quality management system is crucial for ensuring the safety, reliability, and market competitiveness of this construction method [6]. The quality of the prefabricated building design phase significantly affects the subsequent component production and on-site assembly quality. Currently, the design phase faces issues such as asymmetry of design information, inadequate communication leading to increased design conflicts, and the inapplicability of traditional design thinking to prefabricated building design [4,7]. Furthermore, the prefabricated building requires modularization, standardization, and precision, and the current quality management system in the construction industry is only partially suitable for prefabricated buildings.

With the development of building information modeling (BIM) technology [8] and the Internet of Things (IoT) [9], among other information technologies, the quality and

efficiency of prefabricated buildings have been significantly enhanced, making the production of building components more precise and efficient. Particularly, BIM technology offers comprehensive technical support, enhancing management levels, removing barriers in information communication through effective information quality management schemes, and providing new possibilities and directions for improving the quality management of prefabricated buildings [9]. However, while the advantages of BIM technology lie in the richness, shareability, and integration of architectural information, the BIM models still need to be improved by three-dimensional effects and animations and provide an intense immersion and real interactive experience. It is difficult for non-professionals to interpret drawings, models, and data, leading to insufficient feedback on the design. Additionally, virtual reality (VR) technology, as a novel design communication tool, has the advantage of enhanced visualization [10], allowing users to have immersive and interactive experiences in virtual scenes, facilitating design from a human-experience perspective [11] and fully expressing design intentions. However, current research and development mainly focus on hardware devices with most applications being in the realm of the final virtual reality effects.

To overcome the limitations of existing methods, this study proposes a framework that applies BIM and VR integrated technology in the design phase of prefabricated buildings, aimed at assisting architects in process design and outcome expression. This will help improve communication efficiency, reduce design conflicts, and enhance the quality of the design phase, thereby further improving the overall quality of prefabricated buildings.

This study explores critical quality factors in the design phase of prefabricated buildings, addressing quality issues such as fragmented design phases, inefficient collaborative design, and low-level visualization affecting design decisions, and it proposes a quality management framework for the design phase based on BIM and VR technologies. This framework outlines the basic requirements, design work content, and specific application functions of BIM and VR that can be implemented to enhance the design quality across six phases of prefabricated building design. The framework's usability, effectiveness, spatial experience, and functionality are verified through case studies and exploratory sequential mixed methods.

2. Literature Review

2.1. Quality Management of Prefabricated Buildings

The ISO9000 quality management system is an internationally recognized quality management specification system, which is a series of quality management standards issued by the International Organization for Standardization. With the changes in the global market environment, ISO9000 is also constantly developing, and there have been multiple versions since its inception. The latest version is ISO9000:2015 [12]. The international quality standard ISO9000 defines quality as follows: "Quality refers to the degree to which a set of inherent characteristics meet the requirements". ISO9000 is a set of standards that have specific requirements and recommendations for the design and evaluation of management systems. It outlines the quality management framework for organizations to control their internal processes. ISO9000:2015 proposes eight basic quality management principles: customer focus, leadership role, full participation, process approach, system approach, continuous improvement, evidence-based decision making (fact-based decision-making method), and relationship management (mutually beneficial supplier relationship).

Prefabricated building differs significantly from traditional construction in design processes, techniques, and methodologies. There is yet to be a quality management approach, quality control techniques, and an inspection standards system that are comprehensive. The main project participants lack rigorous quality management knowledge [6,13]. Additionally, the variability in production technology and management levels among enterprises makes it difficult to ensure standardized design and regulated construction [14], leading to numerous quality issues at various phases of the prefabricated building industry chain [15].

As a result, an increasing number of governments, associations, scholars, and professionals are focusing on the quality management of prefabricated buildings.

In recent years, scholars have shifted their focus from the technical system affecting the quality of prefabricated buildings to management aspects. Chang et al. [16] used the fishbone diagram method to analyze the critical factors (e.g., management coordination, construction preparation, mechanical operation, and component supply) affecting the quality of prefabricated building construction during the construction phase. Yang et al. [6] established a network model of quality control factors for prefabricated buildings and identified 17 key quality control factors using complex network theory. Masood et al. [17] conducted industry surveys on prefabricated building enterprises to identify quality-related factors from multiple dimensions. Xia et al. [18] used structural equation modeling to assess the impact of quality factors on prefabricated buildings. Zhang et al. [13] developed a quality factor evaluation model for prefabricated buildings. Su et al. [19] explored the quality defects in prefabricated buildings. They constructed a BIM quality management platform supported by the Internet, 3D laser-scanning technology, information processing technology, and mobile app technology. Zhang et al. [20] proposed a blockchain-based traceability system framework for prefabricated component quality.

Some scholars have shifted from a technological system perspective to a management approach, evolving from micro-level specific quality issue prevention to quality management systems and processes. However, most scholars have relied on traditional quality management research methods based on conventional experience, such as PDCA (Plan–Do–Check–Act), SDCA (Standardization Do–Check–Act), etc., and have also conducted related research on quality assessment [13]. The quality of prefabricated buildings is closely linked to various phases. Still, literature reviews reveal that researchers have focused more on quality studies at the construction site [15,16] with less attention to design, production, transportation, and other phases. However, the quality of the design phase determines the overall quality of prefabricated buildings with subsequent construction phases being susceptible to the "butterfly effect" caused by design phase quality issues. Moreover, although some scholars have begun to use the results of information technology development for quality management research in prefabricated buildings, including BIM technology [19,21] and radio-frequency identification (RFID) technology [1], research in this field is scarce and far from systematization. Therefore, fully utilizing the advantages of information technology to address challenges in the design phase of prefabricated buildings, enhancing the quality of the design phase, and further improving overall quality are critical issues that need urgent resolution.

2.2. Application of BIM Technology in the Building Design Phase

With the developing maturity of BIM technology, its application in the information management of prefabricated buildings covers the entire lifecycle, including design, component production and transportation, construction, and operation phases, presenting multi-dimensional data, including design data and time sequences. Furthermore, as design data and quality data are consistent, and the design process aligns with the quality control process, the application of BIM technology in the design phase is not limited to basic tasks like collision checks on drawings. It contributes to resolving conflict, reducing rework, and enhancing design quality [22].

Research indicates that applying BIM technology in the design phase can enhance design quality in the following aspects. (1) Ensuring consistency in design data: The data model in the design phase forms the basis for models in subsequent phases, and parametric modeling data based on BIM technology is fundamental for automated quality assessment systems, containing information like the names, properties, and metadata of building components [23,24]. (2) Facilitating communication among project participants: Compared to traditional processes, using digital technology in building projects can have all the team members collaborate more accurately and effectively, thus improving workflows, design quality, and efficiency [23]. (3) Ensuring consistency in the design process control: By

introducing digital applications, managers can sustainably monitor the execution status of each task in the design process and give professional opinions to ensure the consistency of the quality inspection process in the design process [25]. (4) Enhancing quality management to eliminate defects [26]: By integrating advanced digital technologies linking BIM with VR for quality management, multiple technological approaches can be used to resolve quality issues precisely [27].

2.3. Application of BIM and VR Integrated Technology in the Field of Construction

Over the past twenty years, VR technology has gradually gained increasing attention in the AEC (Architecture, Engineering, and Construction) industry [28]. As an immersive digital technology, VR creates rich virtual environments that allow real-time interaction with digital objects. This technology has been used to solve a variety of design, construction, and operational problems, including design coordination and review, construction education, risk management, safety management, real estate sales [29–31], etc. Multiple studies have shown that VR technology can support design reviews and positively impact the quality of review results [32]. Josef [33] conducted a quantitative analysis and found that more design errors could be detected in VR systems than traditional CAD model engineering design reviews. However, current practical limitations hinder the development of VR applications in the construction industry, such as the lack of rich building information and robust modeling capabilities of VR software.

With the development of technology, traditional BIM-based game engines have expanded into VR systems. VR facilitates interaction with various components and offers participants an immersive experience [34]. Research shows that BIM, as a technology that generates, communicates, and analyzes building models, integrates substantial data, offering rich content resources for virtual simulation technologies [35,36]. VR can create a strong sense of presence and trigger users to behave in real environments [10]. Integrating BIM and VR technologies and analyzing project data using BIM-based game engines can improve the entire construction industry's workflow, enhance communication, understanding, and consensus among project participants at different phases, including improving design processes, reducing misunderstandings, identifying construction hazards, and enhancing safety awareness [12,37,38].

More and more researchers are devoted to exploring the BIM and VR-integrated technology applications in the construction industry. Yan et al. [39] introduced a framework to integrate BIM and VR in construction and its application prospects, including building models, equipment simulation, character modeling, collision detection, path planning, material, and lighting. Du et al. [28] developed an innovative data transfer method, BVRS (BIM, VR Real-Time Synchronization), using a cross-platform cloud infrastructure to create a metadata communication interpretation system, synchronizing BIM data in VR devices in real time and enhancing collaborative work efficiency, thus promoting the applicability of VR technology in the decision making of a construction project. Zheng's [40] research indicated that applying BIM and VR technology in prefabricated building constructions could further refine the entire construction process, improving the overall quality of the project.

While many studies have proposed the application of BIM and VR technology in the construction industry, the overall development of BIM and VR is still very immature. It faces numerous challenges, such as data conversion from BIM to VR, insufficient verification, and limited dissemination of integrated technology. Meanwhile, its utilization is limited to safety management and educational training during construction. Therefore, there is significant scope for research in applying BIM and VR-integrated technology in the construction industry.

3. Methods

3.1. Identification and Analysis of Quality Factors Based on AHP

The Analytic Hierarchy Process (AHP) is a method of hierarchical weighting in decision analysis developed by Thomas in the early 1970s. It is characterized by its systematic and scientific approach. This method decomposes decision-related elements into objectives, criteria, and alternatives. Based on these categories, it facilitates qualitative and quantitative analysis, aiding in analyzing complex issues through digital thinking.

Based on an extensive literature review on prefabricated building quality management, field investigations of prefabricated building projects, and interviews with experts, 17 main influencing factors of quality during the design phase of prefabricated buildings have been identified. Furthermore, the AHP method is used for weight analysis to identify critical factors. The influencing factors of prefabricated building quality are set as the target layer. Human, management, technical, and information factors serve as the index layer. The alternatives layer is composed of the factors mentioned above. The results of the weight analysis are shown in Table 1.

Table 1. Weight of the factors influencing the quality in the prefabricated housing design phase.

Target Layer	Index Layer	Weight	Scheme Layer	Weight	Comprehensive Weight	Ranking
Factors influencing the quality of the prefabricated building design phase	Human factors	0.3319	Professional degree of the designers	0.2212	0.0734	4
			Designer quality and safety training	0.2183	0.0725	5
			Software operating level of the designer	0.2577	0.0855	2
			Experience level of the designers	0.3028	0.1005	1
	Management factors	0.0964	Efficiency and cohesion of the design task quality inspection	0.3546	0.0342	15
			Design unit internal quality management system	0.4735	0.0456	13
			Design the quality supervision system	0.1719	0.0166	17
	Technical factors	0.2476	Normalization of design	0.1835	0.0454	14
			Constructability of the design	0.2053	0.0508	12
			Build the rationality of the split	0.1371	0.0339	16
			The information level of the design	0.2217	0.0549	10
			Design quality requirements are not clear	0.2524	0.0625	8
	Information factors	0.3241	Lack of communication and coordination among various specialties of the design units	0.1755	0.0569	9
			Lack of communication and coordination between the design unit and the component manufacturer	0.2131	0.0691	6
			Lack of communication and coordination between design unit and construction unit	0.2053	0.0665	7
			Timeliness of design change delivery	0.2437	0.0790	3
			The design model was not associated with the quality data	0.1624	0.0526	11

After analyzing the key identified quality factors, the major challenges in quality management during the design phase of the prefabricated building are summarized, including (1) urgent improvement of the designers' professionalism [4]; (2) fragmented design phases leading to inefficient collaborative design management [41]; (3) poorly performed visualization impacting the quality of design decisions; (4) shortage of quality and safety awareness as well as ambiguous quality requirements among design personnel resulting in quality risks.

3.2. Framework for the Application of BIM and VR-Integrated Technology in the Design Phase of Prefabricated Building

By means of analyzing BIM and VR application software and current application status in the design phase of prefabricated buildings, under the guidance of the explored principles of BIM and VR technology integration, this study proposes a framework for applying the BIM and VR integrated technology in the design phase of prefabricated building. This framework can improve the quality of the prefabricated building design phase from the following aspects:

- Utilizing the extensive integrated architectural data of BIM technology and the highly performed visual expression of VR systems to address the two significant challenges in the current designs, the unknown architectural effects and project control difficulties. With this help, errors caused by insufficient design and asymmetric design information will be significantly reduced, and design efficiency and accuracy will greatly improve.
- Adopting a collaborative design platform, integrating highly performed visual and intuitive experiences with continuous interactive feedback during the design process and evaluation, starting from human perception and a first-person perspective. This platform reduces design collisions and blind spots, multi-dimensionally integrates BIM concepts, and reinforces the comprehensive applicability of BIM models, including material rendering, design review, roaming, collision detection, sustainability analysis, etc., thus improving quality management during the prefabricated building design process.
- Integrating VR technology's highly performed visual expression into the design process and using three-dimensional dynamic simulation and interactive experiences. Real project simulations and renderings help compare and optimize different plans, achieving the best design performance.

As shown in Figure 1, the framework outlines the basic requirements, design work aspects, and specific application functions of BIM and VR that can improve prefabricated building design quality in six stages: project planning, conceptual design, initial design, construction drawing design, detailed design, and outcome presentation.

3.2.1. Project Planning Link

After clarifying the project brief and functional requirements, we match the relevant BIM prefabricated model library according to the project type, providing suggestions for prefabricated structural systems. Designers integrate opinions with all stakeholders to create architecture models, use dynamic simulations in virtual scenes for site analysis, and express architectural planning ideas through VR.

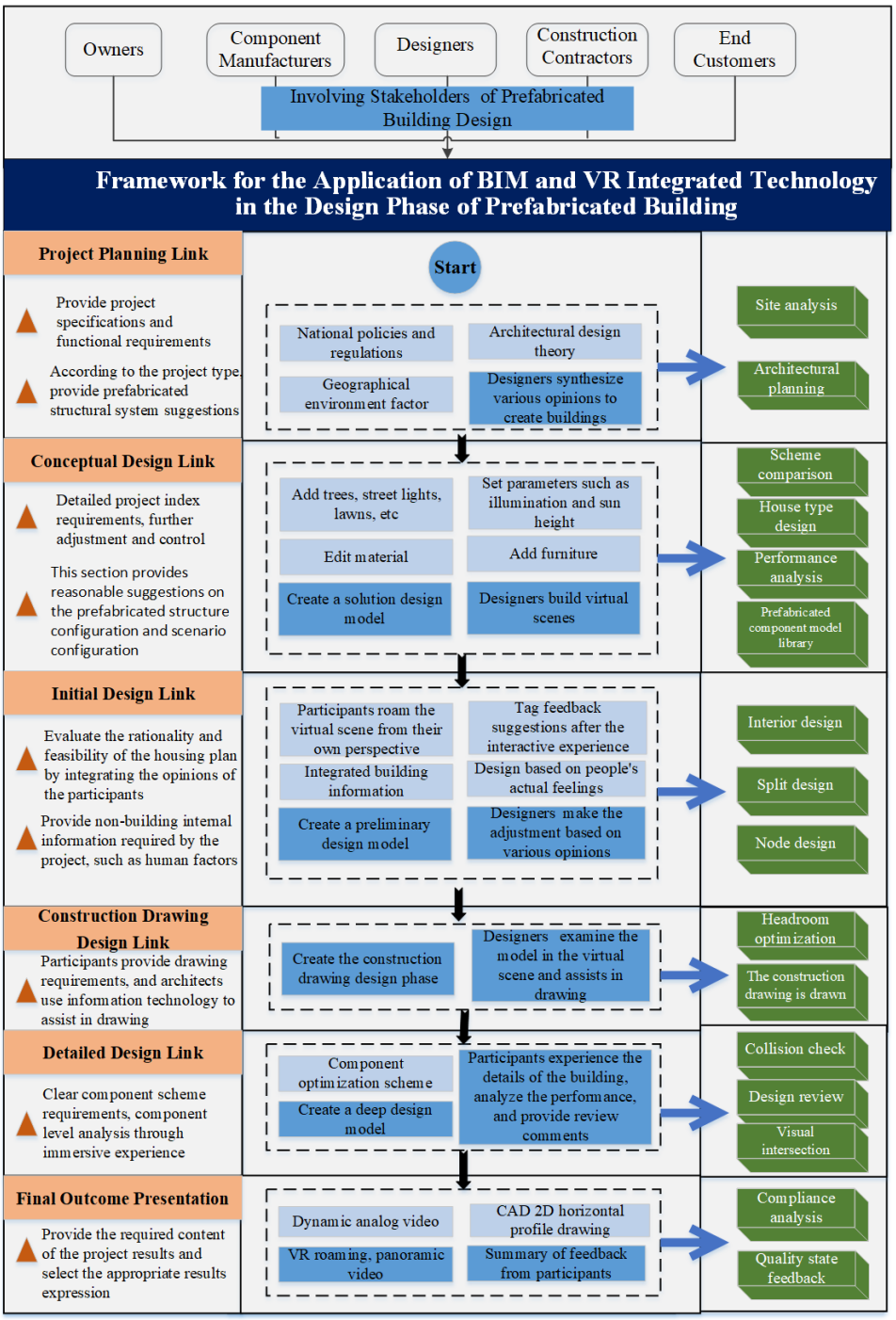


Figure 1. Framework for applying BIM and VR-integrated technology in the design phase of prefabricated building.

3.2.2. Conceptual Design Link

Designers refine project indicators, adjust and control architectural schemes, create scheme design models, and build virtual scenes for the project. This includes adding prefabricated structure configurations, elements like trees, streetlights, and lawns, setting parameters such as lighting and sun elevation, editing materials, adding furniture, etc. Afterwards, designers enter the VR system for an immersive experience, fully engaging sensory functions and spatial perception to realize first-person perspective scheme comparisons and layout selection design work. Meanwhile, the designers utilize the integrated

functionalities of BIM and VR technology to achieve a more comprehensive analysis of building performance.

3.2.3. Initial Design Link

Designers collect internal non-architectural information on project requirements. In design meetings, the designers express design intentions through highly performed visualized VR design models and invite all the project participants to evaluate the feasibility of the architectural schemes in the virtual scenes and give feedback and rational suggestions. To increase user satisfaction with interior design schemes, split design precision, and node designs, the designers interact with different stakeholders (e.g., construction producers, construction contractors, and building users) by using virtual scenes. This method enables the integration of different opinions on adjusting schemes in real time through visual interaction and collaborative design, ensuring the design conforms to real-life situations. In addition, the stakeholders can explore the virtual scenes from their perspectives and feedback through interactive and immersive experiences with annotation features.

3.2.4. Construction Drawing Design Link

The clients and component manufacturers must provide drawing requirements, enabling designers to use BIM and VR technology to create automated drawings, especially detailed and annotated drawings of complex nodes and components. Then, the model collision checks, construction node accuracy inspections, and other design quality checks will be conducted in the BIM and VR environment, and the drawing quality and efficiency will be managed by the BIM and VR technology.

3.2.5. Detailed Design Link

Next, it is necessary to clarify component design requirements to facilitate component design and optimization through VR's immersive experience. On this basis, designers create detailed models; then, the participating experts observe the architectural details with virtual scenes and feedback review opinions, which can ensure a scientific and rational review and make up for perspective and spatial perception defects in two-dimensional drawings and BIM models.

3.2.6. Final Outcome Presentation

Finally, it is important to choose cost-effective outcome expression methods. Architects can conduct VR walkthroughs, publish panoramic videos, and dynamically simulate construction plans using VR software. Through the quality feedback system of the BIM and VR integrated platform, it is possible to collect feedback from all participants to form a specialized program for quality improvement in prefabricated building projects. This involves targeted modifications to the architectural plan, continuous optimization, design error reduction, and design quality enhancement.

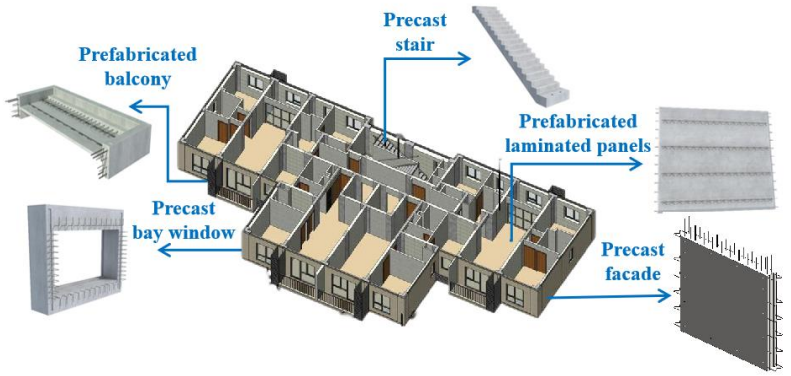
4. Case Study

The Talent Housing Project in Dapeng Center District plots 08-13-04 and 08-13-06 is located in Dapeng New District, Shenzhen, Guangdong Province, China. It covers a total building area of 346,012.6 square meters, including 15 residential buildings with a total residential construction area of about 201,520 square meters. The building project employs standardized design, industrialized production, and prefabricated building. It integrates prefabricated concrete components such as walls, stairs, composite floor slabs, balcony slabs, and assembly construction technologies like aluminum molds and PC interior wall panels. The prefabrication rate exceeds 15%, and the assembly rate exceeds 30%.

4.1. Prefabricated Component Model Library and Model Data Processing

4.1.1. Prefabricated Component Model Library

To better apply the standardized and modular design of prefabricated buildings, it was necessary to build a library of prefabricated house types and component products to achieve the standardization of house types and specification of components, thus reducing the rate of design errors and improving drawing efficiency. This project utilized the design institute's shared cloud drive to build a model database. Initially, components and house types that met the specific requirements of this project were selected from the existing model library. However, since the components and house types in the model library were prototypes, appropriate modifications based on this project were required. Meanwhile, this project's customized components and house types were uploaded to the shared platform, expanding the prefabricated component model library. Figure 2 shows the prefabricated component models, specialized models, and in-depth design models added to the shared platform in this project. The BIM and VR collaborative design platform ensures effective communication and coordination with prefabricated component manufacturers and assembly construction units. It guarantees the models' rationality, applicability, and accuracy, fulfilling factory-standardized production and assembly construction requirements.



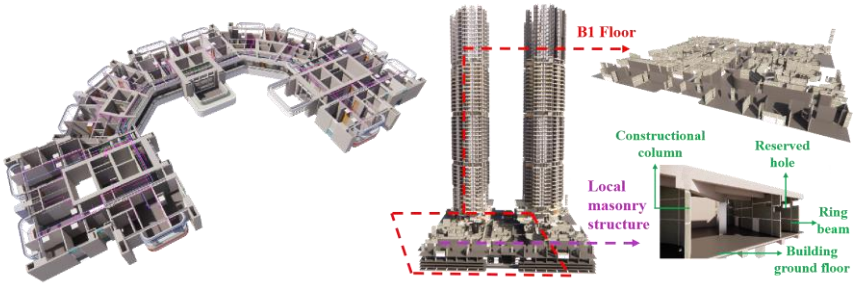
(**a**)



Structural model Building model Electromechanical model

(**b**)

Figure 2. *Cont.*



(**c**)

Figure 2. (**a**) New precast component model and standard layer design for this project; (**b**) three-dimensional models of various disciplines in the project; (**c**) the deepened design model of this project.

4.1.2. Processing and Conversion of Model Data

A vital issue in BIM and VR-integrated technology is resolving the compatibility of different data formats, since the model data processing and conversion are crucial. The VR software Fuzor 2020 chosen for this case supports multiple formats such as .fbx, .che, .exe, and .skp. As shown in Figure 3, different professional data models were constructed by Revit software at first, and then the model data were directly imported into the VR software via an add-on module. The viewpoints of the BIM model and VR scene model were synchronized, and the model data could be modified and updated in real time from both directions.

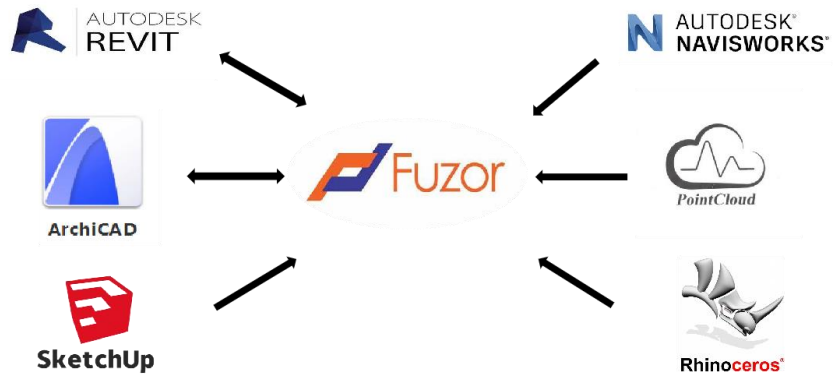


Figure 3. Data modeling software supported by the Fuzor platform.

4.2. Interior Scheme Design and Scene Design

4.2.1. Interior Scheme Design

From conceptual to interior design, the BIM and VR-integrated technology allows project participants to immerse themselves in a walkthrough of the building. Using the family library in Fuzor 2020 software, different interior design options are quickly created for selection and synchronized with BIM modeling software. The triggering system in VR software enables switching between different interior design schemes in the virtual scene, including various layouts, families, and materials. The VR visualization feature allows users to truly experience natural elements like sound and light, spatial dimensions and materials of the site and building, and the size of the furniture, thus aiding in selecting the best design scheme, as shown in Figure 4. Applying BIM and VR technology enables users to view and obtain BIM-based data in the virtual environment and quickly switch to the component properties window to review BIM information such as materials, sources, and dimensions. After receiving basic property information, the relevant stakeholders can

review the model information professionally. They used the annotation feature to mark and give feedback where they had doubts, assisting designers in further modifying the scheme.



(**a**) Interior Design Plan A



(**b**) Interior Design Plan B

Figure 4. Selection of different interior design schemes based on BIM and VR-integrated technology.

4.2.2. Scene Design and Material Selection

On the foundation of the BIM model, the VR software's powerful library is used to construct scene settings and build roaming scenarios in the virtual environment, such as cars, trees, reflections, etc., enhancing the visual richness in the roaming experience. The integrated technology platform features a powerful material editor and library. Participants can simulate switching different materials on the same component using the trigger function, obtaining a realistic experience, providing feedback, and then selecting the best material solution. BIM and VR-integrated technology not only simplifies the process of enhancing materials but also avoids design decisions based on designers' perspectives, increasing the applicability and rationality of material enhancement, as shown in Figure 5.



(**a**)



(**b**)

Figure 5. (**a**) Scene construction based on BIM and VR integrated technology; (**b**) material selection based on BIM and VR.

4.3. Visual Collaborative Design

Compared to the traditional collaborative methods and BIM-based methods, BIM and VR collaborative design can realize speedy uploading of the model to the cloud and instant sharing with relevant personnel. The stakeholders can roam in the virtual scenes to annotate design feedback, directly observe the overall model and detailed constructions, and verify design model errors through collaboration with various specialties. Additionally, BIM and VR models are bidirectionally interconnected. Model modifications can be made at any stage during the prefabricated building design phase, no matter the changes in objects or contents, which synchronously will be linked between the two models.

4.4. Design Check

4.4.1. Collision Check

When the project participants roam in real time within the 3D model and virtual scenes, they can observe the overall model and inspect detailed components or nodes, using the collision detection feature of the VR software, which can examine unreasonable collisions both within and between specialties as well as generate detection reports including location,

quantity, parts, materials, etc. As shown in Figure 6, through collision checks based on BIM and VR-integrated technology, over 86 collisions were identified and resolved.

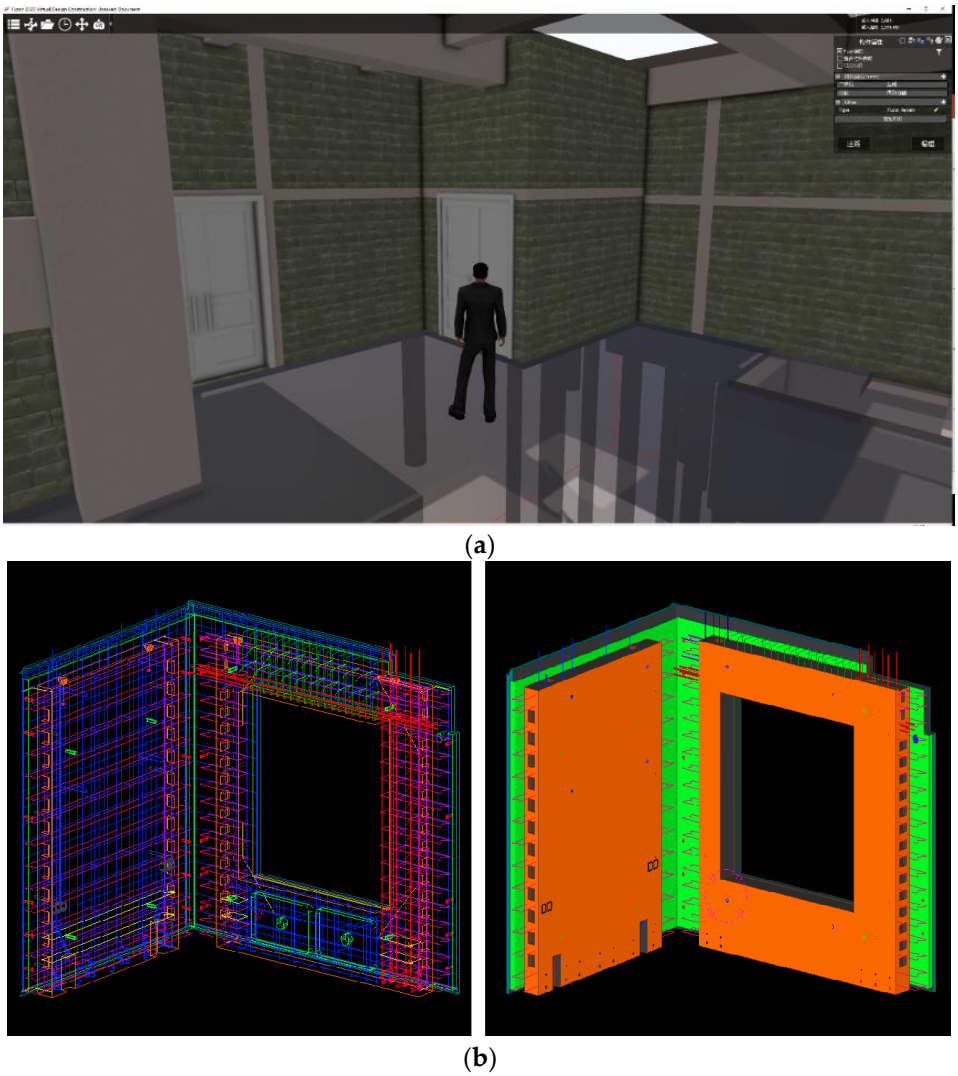


Figure 6. Collision inspection based on BIM and VR integrated technology. (**a**) Roaming in a virtual environment to check; (**b**) prefabricated component connection problem.

4.4.2. Design Review and Quality Status Feedback

For model construction, detailed attribute information of components, including dimensions, shape, materials, etc., was entered to form the foundational data of the architectural model. During the prefabricated building design phase, participants utilized BIM and VR visualization technology to roam in the architectural space and view the input information in real time. They comprehensively verified the accuracy and rationality of schemes and models through real human experiences, continually discovering issues through interaction and experience and entering feedback via the annotation function. Additionally, the annotation and issue-tracking features can mark and track design issues with different methods, such as taking snapshots, making marks, and adding comments. They can categorize design issues to assign to respective responsible parties. BIM and VR-integrated technology enables exporting annotation reports, including specific component models and locations, annotators, annotation contents, etc., facilitating designers to view feedback on design quality from all participants and to locate this feedback within the model for a comprehensive analysis of quality issues, optimizing the scheme.

4.5. Outputs

After creating the architectural model and virtual scene, the HTC Vive VR headset was connected to the Fuzor 2020 platform. Participants held controllers and wore the headset to engage in an immersive VR experience. The realistic immersion and rich roaming experience provided by BIM and VR-integrated technology enabled even non-professionals to intuitively view design outcomes, thoroughly explore prefabricated building design schemes, and completely grasp the design intentions. After finishing the design, designers produced drawings and exported two-dimensional plans, elevations, and sections.

5. Results and Discussion

5.1. Testing and Evaluation

To evaluate the developed framework, an exploratory sequential mixed method is adopted, involving stakeholders (n = 24) from different stages of prefabricated building design, including designers, component manufacturers, construction contractors, owners, and customers. The main testing contents include the following:

- System Usability Scale (SUS): 10 Likert-scale questions scored out of 5 [41], encompassing positive and negative aspects.
- Objective Performance Evaluation: Through controlled experiments comparing this method with two existing traditional design methods, the usability of this method is quantitatively analyzed. It mainly compares and examines the number of design errors detected in collision tests and the number of design errors or queries raised in drawing reviews during the design evaluation phase of prefabricated buildings.
- Open-Ended Interview Theme Analysis: Following the principle of voluntariness, 15 stakeholders who had participated in the survey questionnaire were invited for open-ended interviews and theme analysis, aiming to evaluate the usefulness, functionality, spatial experience, and challenges of the method.

Before the test, participants were required to complete the introductory part of the questionnaire, which captured their background information such as occupation, age, gender, experience in construction projects, and experience with virtual reality (Table 2). Additionally, participants were briefly introduced to the functionalities of BIM and VR-integrated technology, including the user interface and other interactive features. Subsequently, each participant was given 20 min to test the interior design, scene setup, material selection, and design review tasks.

Table 2. Background information of test and evaluation participants.

Participant ID	Gender	Age [a]	Role	Previous VR Exp.	Previous BIM Exp.	Construction Experience (Unit: Year)	Participate in the Interview
PA 1	M	36	Owner	√	√	14	√
PA 2	F	43	Owner	√	√	23	
PA 3	M	39	Owner	×	√	16	
PA 4	F	52	Owner	×	√	27	√
PA 5	F	33	Designer—Architecture	√	√	8	√
PA 6	F	55	Designer—Structural Engineering	×	√	31	√
PA 7	M	44	Designer—Architecture	×	√	20	√
PA 8	M	31	Designer—Architecture	√	√	9	

Table 2. *Cont.*

Participant ID	Gender	Age [a]	Role	Previous VR Exp.	Previous BIM Exp.	Construction Experience (Unit: Year)	Participate in the Interview
PA 9	F	26	Designer —Structural Engineering	√	√	2	√
PA 10	F	27	Designer —Plumbing	√	√	4	√
PA 11	M	23	Designer —Electrical Engineering	√	√	2	√
PA 12	M	29	Designer —Electrical Engineering	×	√	2	
PA 13	F	38	Designer —HVAC Engineering	√	√	16	√
PA 14	F	26	Component Manufacturer	√	√	5	√
PA 15	F	31	Component Manufacturer	×	√	10	
PA 16	F	34	Component Manufacturer	×	×	16	√
PA 17	M	29	Component Manufacturer	√	√	7	
PA 18	M	27	Construction Contractor	√	√	6	√
PA 19	F	25	Construction Contractor	√	√	3	
PA 20	F	31	Construction Contractor	√	√	10	
PA 21	F	45	Construction Contractor	×	√	26	√
PA 22	F	52	Customer	×	×	/	√
PA 23	M	32	Customer	√	√	/	√
PA 24	F	38	Customer	×	√	/	
PA 25	F	44	Customer	√	√	/	
PA 26	M	37	Customer	×	×	/	

[a] The average age of the participants is 35.6 years old.

5.2. Reliability of the Evaluation Tool

The survey results fall under the category of an attitude scale. In quantitative analysis, reliability analysis assesses the credibility of the survey research, referring to the extent to which the tool can produce the same results when it is measured again under the same conditions. Typically, CA (Cronbach's alpha) is used to calculate the reliability of the scale. Brade [42] considers a CA value greater than 0.70 to be reliable for a questionnaire. In this study, the standardized System Usability Scale (SUS) was used, with a reliability of 0.91 [41], indicating that the questionnaire is reliable and possesses sufficient internal consistency.

5.3. Usability Evaluation

5.3.1. Objective Performance Evaluation

The objective performance indicators in the usability evaluation reflect the actual results that occur during the user's interaction with the product. As a quantitative analysis method for user operation behavior, it typically includes the analysis of task completion accuracy, task completion rate, task completion time, error frequency, and other metrics to assess the product's usability level. These are presented in the form of visualized data, directly reflecting the interaction results between the user and the product. Furthermore,

it often garners more attention from corporate executives and project stakeholders as a quantitative usability evaluation indicator.

Three prefabricated residential buildings from the above-mentioned case study were selected, having identical structural forms, standard floor areas, and other design elements. This study invited the design team of the case project to conduct an objective performance evaluation, including designers from five specialties: architecture, structure, plumbing, electrical, and HVAC. They used three different design methods for these three prefabricated residential buildings through controlled experiments, and at the same time, they recorded and summarized the collision detection and drawing review results of each profession. As shown in Table 3, the design method using BIM and VR-integrated technology increased the number of identified design collisions by 28.35% compared to using BIM technology alone. Regarding to drawing reviews, compared to the traditional 2D drawing design method, the number of design issues was reduced by 41.35% with BIM and VR-integrated technology, and it was dropped by 15% with the BIM-based design method alone.

Table 3. Collision detection and drawing review results of various design specialties under different design methods (unit: article).

Methods	Design Task	Architecture	Structural Engineering	Plumbing	Electrical Engineering	HVAC Engineering	Total
2D drawing	Collision Detection	/	/	/	/	/	/
	Drawing Review	34	18	22	39	20	133
BIM	Collision Detection	7	16	11	20	13	67
	Drawing Review	26	15	14	23	14	92
BIM and VR	Collision Detection	19	17	12	23	15	86
	Drawing Review	18	14	12	21	13	78

The results showed that using BIM technology alone and VR-integrated technology could reduce the amount of feedback on design errors or queries during the drawing review phase across the five major disciplines, especially in plumbing, electrical, and HVAC specialties. However, the BIM and VR-integrated method could further reduce these numbers, especially in architecture. It validates the advantages of this method's high degree of visualization and enhanced architectural space experience in reducing the number of design errors or queries. By utilizing this design method, participants, including customers, are invited to engage in the design proposal at an early stage, keep continuous communication, and provide their feedback and experience throughout the design phase. It will be beneficial to understand the designer's intent and avoid collisions and design errors during the architectural design and project implementation, ensuring the overall integrity of the design.

5.3.2. System Usability Scale Evaluation

The System Usability Scale (SUS) was first published in 1986 and included 10 statements, comprising five positive and five negative descriptions. This scale employs a 5-point rating system ranging from "strongly disagree" to "strongly agree". The user's final responses will be converted into a percentage score. The calculation formula is $[\Sigma(\text{positive description score} - 1) + \Sigma(5 - \text{negative description score})] \times 2.5$ (where 1 represents strong disagreement and 5 represents strong agreement). With an increment of 2.5 points, SUS scores range from 0 to 100. Research indicates that SUS applies to device systems and products that interact with users, providing an SUS score that is not significantly different from more extensive sample measurements even with a few samples.

Brooke [41] and his colleagues, based on their analysis of 206 SUS usability questionnaires, have scientifically interpreted the final score categories of the questionnaire. An SUS score of less than 50 indicates that users find the usability of the tested system or product unacceptable. If the SUS score is between 50 and 70, it implies that the usability of the

system or product is within an acceptable threshold for users. Conversely, an SUS score above 70 suggests that users are satisfied with the usability of the tested system or product.

By executing the SUS analysis procedure, this study achieved an average score of 78, which is higher than the 70 suggested by Brooke [41]. Therefore, the usability level of this framework falls within the range acceptable to users, indicating a generally favorable reception. Table 4 presents the results of this usability test, retaining the original average scores for the negative items. It shows that the scores received for the five positive descriptions ranged from 3.82 to 4.43. The questions with the highest score address that various functions in this system were well integrated (U5, M = 4.43, SD = 0.87), and users felt very confident using the system (U9, M = 4.15, SD = 0.79). Subsequently, most people learned to use the system very quickly (U7, M = 4.07, SD = 0.85) and would like to use this system frequently (U1, M = 3.94, SD = 0.77). The positive assertion with the lowest score questioned whether the system was easy to use (U3, M = 3.82, SD = 0.95).

Table 4. The SUS evaluation results.

Number	System Usability Scale Items	M	SD
U5	I found the various functions in this system were well integrated.	4.43	0.87
U9	I felt very confident when using the system.	4.15	0.79
U7	I think most people will learn to use this system very quickly.	4.07	0.85
U1	I will frequently use this system.	3.94	0.77
U3	The system is easy to use.	3.82	0.95
U10	I need to learn a lot before I can get going with this system.	2.13	0.74
U4	I need support from a technical person to use this system.	2.04	0.68
U6	There are too many inconsistencies in this system.	1.88	0.76
U8	The system is cumbersome to use.	1.67	0.91
U2	The system is unnecessarily complicated.	1.40	0.83

The negative assertions are in the bottom half of Table 4. That is, lower scores correspond to better evaluation. In the sequence, less disagreement (more negative evaluation) occurred regarding the need for the user to learn many things before getting going with the system (U10, M = 2.13, SD = 0.74). Participants partially disagreed that they would need a technical person's support to use this system (U4, M = 2.04, SD = 0.68), and the system needed more consistency (U6, M = 1.88, SD = 0.76). Finally, the items with the most disagreement (more positive evaluation) refer to the system as very cumbersome to use (U8, M = 1.67, SD = 0.91), and the system could have been more complex (U2, M = 1.40, SD = 0.83).

5.4. Open-Ended Interview Theme Analysis

Considering the particularity of this study and the need for participants to have a professional knowledge background in prefabricated building design tasks, this study used convenience sampling combined with the snowball method to recruit interview participants, ensuring that the number of participants invited was small but the correlation was high. The participants were invited by the researchers via social network email, and they followed a voluntary principle. Finally, 15 stakeholders who participated in the research survey were invited for open-ended interviews. This group included seven designers, two component manufacturers, two construction contractors, two property owners, and two end customers. The collected interview data were subjected to thematic analysis, which is often considered the most effective method to convert qualitative data to extract valuable information. The primary objective of the interviews was to further explore the usability of BIM and VR-integrated technology in the design phase of prefabricated buildings to improve the design quality. There were four core questions of the interview:

- What advantages have you found in prefabricated building design using BIM and VR-integrated technology compared to traditional design methods? (Effectiveness)
- Can this method improve the quality of the design phase? (Functionality)

- How is the spatial experience different from this method compared to traditional design methods? (Spatial Experience)
- What challenges do you think will arise from the comprehensive application of this method? (Challenges)

5.4.1. Effectiveness

All participants (n = 15) believe that BIM and VR-integrated technology effectively enhanced the quality of the design phase in prefabricated building projects, which was mainly reflected in three aspects:

(1) Improvement of Design Tools. Participants (n = 12) believed that this method optimized the 2D drawing output process, enabling the automatic export of detailed component drawings, construction node details, design annotations, and other complex drawings. This method also enhanced the accuracy and precision of prefabricated building design drawings, aiding in comprehensive quality control of design drawings at the design phase. Participants (n = 8) expressed that project stakeholders could effectively select different design outcomes per their needs, enhancing the comprehensiveness and objectivity of the final design review and providing a solid foundation for project communication in subsequent construction and operation phases. Participants (n = 3) mentioned, "This method requires BIM model data to support import, reading, conversion, and output functionalities, demanding richness, integration, and uniformity in model data. This will stimulate the number and scope of collaborative design software, supporting collaborative design development in the prefabricated building."

(2) Optimization of Workflow. Participants (n = 11) believed that the design environment created by BIM and VR-integrated technology provided a platform for real-time design participation and immersive virtual reality experiences for all project stakeholders and the public. This enabled different roles to fully engage in the design process, offering real-time feedback on professional opinions and fostering the development of multi-threaded workflows. Therefore, it avoided common issues in traditional design methods, such as frequent design conflicts, lengthy coordination meetings, delays in design change communication, and significant discrepancies between drawings and models, severely affecting the quality and efficiency of prefabricated building design.

(3) Shift in Design Thinking. Participants (n = 8) believed this method had led to a shift toward holistic thinking and a lifecycle awareness among designers. Specifically, in the early design phases, when a virtual site was created, the designers would take environmental factors (e.g., sunlight, sound, and wind) into account to propose project planning solutions; in subsequent phases like scheme design, preliminary design, and construction drawing design, there was a continuous "communication-dialogue" with the architecture, finalizing design contents based on real human experiences and refining the design proposals. After the design proposals were completed, the integration of models, simulations, and immersive experiences was used to test the feasibility of the plans to select the best building materials and interior design furniture, focusing on user experience feedback. Participants (n = 5) also mentioned that the design process now included simulations and considerations for construction feasibility and operational maintenance, contributing to the lifecycle development of prefabricated buildings.

5.4.2. Functionality

All participants (n = 15) gave positive feedback on the method's quality improvement capabilities. Specifically, the complete application of BIM and VR-integrated technology in the design phase of prefabricated building projects is beneficial for focusing on and enhancing design outcomes. In addition, six designers, one component manufacturer, one construction contractor, two property owners, and one end customer (n = 11) further

noticed that this method emphasized procedural design and evaluation, continuously improving design quality to enhance overall quality.

(1) Participants (n = 9) believed that starting from the project research and planning phase, inputting relevant data of the building project into the virtual scenes helped enhance the scientific nature and accuracy of the architectural scheme.
(2) Participants (n = 13) believed that this method, based on the highly performed visualization of VR technology, allowed design participants of various roles to provide realistic architectural requirements from their perspective, such as clients' requirements on overall project planning and architectural design, the designer's consideration of architectural aesthetics, the structural engineer's validation of structural reliability, and the public's daily needs for building functionality. This is conducive to managing the overall integrity of the design, improving work efficiency and quality.
(3) Participants (n = 8) believed this method had increased public participation and influence. This method went beyond just the project planning research phase, since it allowed experiencing the architectural functionality from a first-person perspective and enabled the public to contribute design opinions and everyday life needs. Incorporating public feedback and real human experience design improved the final product's acceptability and increased product satisfaction.
(4) Participants (n = 15) believed that by using the collaborative design platform of BIM and VR-integrated technology, the stakeholders could maintain continuous communication, provide feedback, experience, and interact throughout the design process, which would avoid collisions and "blind spots" between architectural design and project implementation, preemptively eliminate design errors and significantly enhance the quality of prefabricated building design.

5.4.3. Sense of Space Experience

Participants (n = 15) provided feedback on the spatial experience in the BIM and VR-integrated technology design environment, as shown in Table 5. Through profound, immersive experiences, designers could interact with architectural spaces in real-time visually, audibly, and within a virtual reality environment, reading design data and annotating design opinions. They could simulate different perspectives, heights, walking paths, and movement speeds to create a realistic environment and reinforce the expression of design intent. Moreover, design errors could be reduced by integrating with the BIM collaborative design platform for managing architectural data.

Table 5. Spatial experience of different design methods.

Methods	Functional Use		Sensory Function				Spatial Function		Construction Information	Real-Time Interaction
	Static State	Dynamic State	Vision Sense	Auditory Sense	Tactile Sense	Gustation	Reality Space	Virtual Space		
2D drawing	√		√				√		√	
BIM		√	√				√		√	
BIM and VR	√	√	√	√	Develop	Develop	√	√	√	√

5.4.4. Challenges

Participants (n = 12) identified challenges and limitations when fully implementing this method. Seven participants expressed that the BIM and VR collaborative design platform needed further development, particularly in enhancing the core performance of collaborative software and platforms, including the integrity of data model conversion between different design software and the convenience of operation in immersive experiences. Five participants pointed out that conventional design thinking poses a significant challenge. Design teams opted for familiar workflows and design methods in prefabricated building projects without precise requirements to use new information technologies. This

typically involved creating 2D drawings via CAD for construction design and then using BIM software to convert these drawings into 3D models, rendering architectural visuals, and simulating construction animations.

Participants (n = 3) mentioned that VR technology still had many application limitations, highlighting two aspects: first, project stakeholders and designers tend to use VR technology only as a tool for representation, focusing excessively on high-quality renderings, realistic lighting, and rich scenes without paying attention to its potential in facilitating rational choices for functional layout, optimizing interior design, and adjusting site planning through experiential feedback. The second aspect is the imperfection of VR systems and the high hardware cost, which places specific requirements on the project team's computer specifications, graphics card models, head-mounted devices, etc., increasing project costs. Additionally, there are many "novices" among VR designers in the construction industry, and the lack of a unified standard for VR systems increases the risk of project delays.

6. Conclusions

Through an analysis of critical quality factors in the design phase of prefabricated buildings, this study addresses issues such as fragmented design phases, inefficient collaborative design, and poorly performed visualization impacting decision-making quality. Also, this study proposes a solution based on BIM and VR-integrated technology and creates a quality management framework for the prefabricated building design phase. This framework outlines the fundamental requirements, design work contents, and specific application features of BIM and VR that can promote design quality across six phases of the prefabricated building design: project planning, scheme design, preliminary design, construction drawing design, detailed design, and outcome presentation. Applying this framework to a prefabricated building project in Shenzhen, China, it was found that compared to traditional 2D drawing methods, the design issues feedback during drawing reviews decreased by 41.35%. Compared to using BIM technology alone, the number of design collisions identified through collision detection increased by 28.35%, and feedback on design issues during drawing reviews decreased by 15%. Furthermore, testing the proposed framework among different construction stakeholders using an exploratory sequential mixed method validated its usability, effectiveness, spatial experience, and functionality. The framework, combining the rich architectural information of BIM and the immersive experience of VR, contributed to focusing on the design process, improving design tools, optimizing workflow, significantly reducing design errors and promoting the quality of prefabricated buildings.

Several directions are worth further research: (1) addressing data conversion integrity, compatibility, and convenience between BIM and VR software from theoretical and application perspectives; (2) further exploring the application of BIM and VR-integrated technology in other phases of the prefabricated building's lifecycle; and (3) further integrating augmented reality and mixed-reality technologies to expand the practical application of this method in quality management during prefabricated building design phases.

Author Contributions: Conceptualization, B.Y.; Methodology, M.Z. and J.W.; Validation, K.C.; Formal analysis, K.C.; Writing—original draft, M.Z.; Writing—review & editing, B.Y.; Supervision, B.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Min Zhou was employed by the company China Construction Eighth Engineering Division. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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