Application of BIM and Virtual Reality of System Integration Design and Development in Medical Building Projects: A Case Study in China

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Abstract

Design outcomes in the Medical Building Projects (MBPs) must satisfy the demand of the medical staff and stakeholders. However, they often do not have the relevant engineering expertise, so the design team is prone to misunderstandings when communicating with them using traditional two-dimensional (2D) Computer-Aided Design (CAD) drawings. The medical staff may not readily visualize and understand the design and then provide feedback to the designer through professional medical requirements or advice, which results in the need to redesign and carry out additional work during the design phase, thus delaying the progress of the MBPs. To address these challenges, this study aims to develop an integrated system based on BIM, advanced rendering engines, and VR technology for use in non-immersive and immersive VR environments. Moreover, in this study, the integrated system was applied to the infection-building project of the People's Hospital of Qingbaijiang District, Chengdu City, and semi-structured interviews were distributed to 16 engineers, designers, contractors, and medical staff who had been involved in the whole project to validate the practicality and effectiveness of the integrated system. The results indicate that this system integration is an efficient visual communication and simulation tool in medical design. Key advantages include enhanced communication efficiency between the design team and medical stakeholders, improved visual interaction, and streamlined decision-making processes within a 3D VR/BIM environment. The successful implementation of this integrated system is expected to significantly aid design teams and stakeholders in effectively managing medical design tasks in future projects.

Keywords: Building Information Modeling (BIM), Medical Building Projects (MBPs), Virtual Reality (VR), Design.

1. Introduction

Medical Building Projects (MBPs) are initiatives encompassing the design and development of medical facilities for medical care provision. Due to their specialized character, intricate processes, profound design, and interdisciplinary interactions, medical construction projects exhibit high complexity [1],[2]. In conventional design approaches, design teams employ two-dimensional (2D) Computer-aided Design (CAD) drawings and pertinent information to articulate the design intentions for medical staff [3],[4]. However, due to a dearth of engineering expertise and experience, it poses a challenge for medical staff to comprehend the concepts and contents conveyed through these 2D CAD drawings [5].

Concurrently, the application of Building Information Modeling (BIM) has emerged as a prominent trend within the medical building construction sector [6]. BIM, which functions as a knowledge center and shared database, has

demonstrated its utility in the visualization, integration, and analysis of the physical and functional attributes of constructed entities throughout the entirety of the building lifecycle, encompassing design, construction, operation, and maintenance [7]. As a vital communication platform, BIM technology enables the simulation of construction design and construction information [8]. BIM has revolutionized building design and delivery processes in numerous ways, particularly in the construction of highly complex structures such as medical facilities [9],[10]. BIM, a mature tool employed during the design phase, has recently been utilized in MBPs [11]. The digitization of medical facilities can serve as a potential instrument for leveraging BIM technology in hospital architectural strategic development [11]. BIM technology enables medical clinical staff to interact virtually with spaces, allowing them to offer valuable feedback [5].

Driven by the widespread adoption of BIM technology, earlier research has greatly focused on studying BIM technology applications in solving Architectural, Engineering, and Construction (AEC) issues. For example, Lu et al. [12] investigated the uses, purposes, and evaluations of BIM in assisting the creation of green buildings. Wang et al. [13] investigated the implementation of BIM and Geographic Information Systems (GIS) in the context of sustainable built environments. They also presented four relevant applications, namely energy management, data integration, lifecycle project management, and urban governance.

Despite the extensive application and research focus on BIM technologies for AEC projects, their integration into medical building design has garnered limited attention. Furthermore, many researchers have used Virtual Reality (VR) technology to enhance design communication in general buildings, however; few studies have focused on MBPs. Lin, et al. [14] developed a database-supported VR/BIM-based communication and simulation (DVBCS) system integrating BIM, game engine, and VR technologies for healthcare design in semi-immersive VR environments. The DVBCS system was applied to a case study of a cancer center design project in Taiwan, validated the system, and demonstrated its effectiveness in practice. Buchanan, et al. [15] evaluated whether virtual reality (VR) could be used to display building information modeling (BIM) metadata as well as spatial data in a virtual environment and, in doing so, determined whether improvements could be made to enhance design review effectiveness participant understanding of the design. Ultimately, the results of this study demonstrated that VR technology has a higher rate of task completion, and that VR technology also improves the effectiveness of design reviews conducted by healthcare professionals. Akçay, et al. [16] suggest that BIM and immersive VR visualization have task-specific advantages over traditional design and project development methods for solving complex design problems in large hospitals, but they also face significant challenges.

The difference between this study and previous related studies is that the non-immersive VR in this study integrates a better rendering engine, which not only allows for faster and more realistic rendering but also allows for VR environments to be experienced anytime, anywhere, using convenient devices such as mobile phones or iPads. In addition, the immersive VR benefits from the combination of Fuzor and Revit software, which makes it easier for medical staff to view the detailed build information and collision conditions of the BIM model. The primary aim of this research was to develop an integrated system that merges BIM, advanced rendering engines, and VR technologies, designed specifically for use in the design phase of MBPs. Finally, the infection ward construction project of Qingbaijiang District People's Hospital in Chengdu, China, was taken as an example to verify the system and demonstrate its effectiveness in practice.

2. Literature review

Medical facility projects are of the utmost importance to society, as they deliver essential medical support and patient care. In addition to specialized design consultants, MBPs require stakeholders' and medical staff's involvement throughout the design review process. Medical staff and the stakeholders are required to provide feedback and "sign off" design decisions. Design reviews typically consist of a 2D CAD drawing package (building plans, sections, elevations), technical specifications, and a few 3D images that stakeholders must review and comment on. Due to a lack of specialist understanding in architecture or engineering, stakeholders and medical staff sometimes find 2D drawings difficult to read. [14]. This results in bad design judgments and inescapable miscommunication between the medical staff and the design team. As evidenced by research, patient health is significantly influenced by the quality of the constructed environment; hence, an unsatisfactory design outcome has beyond mere cost implications [17],[18]. The implementation of cutting-edge digital technologies, including BIM and VR, is crucial for medical design teams to ensure the efficacy of a design review tool tailored to the precise requirements of MBPs [19],[20].

Notably, in recent years, an escalating focus has been placed on the amalgamation of BIM and VR within the AEC sector [21]. The idea of VR emerged over 50 years ago with the creation of the first immersive human-computer interaction (HCI) prototype, known as the "Man-Machine Graphical Communication System" [22]. The term "Virtual Reality" was officially coined in 1989 [23].

In recent years, VR and construction industry-related research have gradually increased. For example, VR applications have the potential to significantly enhance the decision-making efficiency and accuracy of quantity surveying work by facilitating practical navigation through virtual 3D building models for quantity surveying practitioners and students, thereby fostering a deeper understanding of architectural design [24]. The fusion of BIM technology and VR technology has the potential to augment collaboration, streamline workflows, and aid inexperienced personnel in comprehending the design objectives of the project team [25]. Integrating BIM and VR technologies in a standardized protocol can effectively enhance construction safety training, as demonstrated by a practical application in an Italian construction project [26]. 4-Dimensional BIM (4D BIM) and VR significantly improve hazard recognition, understanding of safety protocols, and proactive risk response among multilingual construction crews [27]. New technologies such as Augmented Reality (AR) and VR are increasingly used in construction projects to enhance preventative safety, productivity, and quality [28-30].

3. Research Methodology

This study meticulously examined the integration of BIM, advanced rendering engines, and VR technologies during the design phase of the infectious disease ward construction project at Qingbaijiang District People's Hospital in Chengdu, China. The project was funded by the government and utilized the Engineering Procurement Construction (EPC) model contract type, which was awarded to CITIC Architectural Design & Research Institute Limited and China Chemical Engineering Sixth Construction Company Limited as a consortium. CITIC Architectural Design & Research Institute Co., Ltd. was responsible for the traditional 2D design, while China Chemical Engineering Sixth Construction Co., Ltd. was responsible for the creation and deepening of the BIM model as well as the construction of the project. This high-rise medical building, encompassing 5,107 square meters and standing at a height of 53.3 meters, began construction on June 30, 2021, and concluded on December 31, 2023, with a budget

of 208 million RMB. The building, covering 35,776 square meters, comprises a 12-story above-ground medical structure, underground parking, civil defense facilities, and utility rooms. The overall layout of this infection-building project is illustrated in **Figure 1**. It's structured to efficiently accommodate outpatient services, medical technology, and inpatient care.

The project was characterized by intricate medical design requirements, necessitating constant design revisions to meet the evolving needs of the hospital owner. This complexity, coupled with a stringent construction schedule and high safety and quality standards, underscored the importance of employing BIM and VR technologies in the design phase. As a result, it is critical for construction firms to use BIM and VR technology during the design phase of MBPs.

Figure 1 The overall layout of this infection-building project.

The core objective of this research was to explore the benefits of BIM and VR applications in the design stage of medical construction projects. By incorporating these technologies, the study aimed to enhance communication efficiency among various stakeholders, including designers, engineers, contractors, medical staff, and other involved parties. This was expected to facilitate better visual interaction and streamline decision-making processes within the 3D VR/BIM environment.

Additionally, this study builds on the research by Lin et al. [14] and conducted comprehensive semi-structured interviews to rigorously assess the effectiveness and satisfaction with the integrated system. The study involved 20-minute online video interviews with each expert via the "Tencent Meeting" software. Sixteen experts (including four designers, four engineers, four contractors, and four medical personnel) were invited to rate the effectiveness and satisfaction of using BIM+VR technology during the MBPs design phase using a five-point Likert scale (where 1 represents very dissatisfied and 5 represents very satisfied). Data analysis was performed using Excel. The study aimed to gather their opinions on the system's functionality, efficiency, stability, and overall satisfaction, as well as their willingness to use the system for communication during the design phase. This method aids in a comprehensive assessment of the system's impact on the project.

4. System Integration design and development

The creation process of the integration of the virtual reality application system is illustrated in **Figure 2**, distinguishing between non-immersive systems (desktop VR) and immersive systems (head-mounted displays). The VR application system integration required for this study requires a combination of Autodesk Revit 2020, Cinema 4D R19, Fuzor 2020, and the 720-Cloud platform.

The first step is creating corresponding 3D models based on 2D CAD drawings in Autodesk Revit 2020, which allows designers of different disciplines to integrate and collaborate on multi-disciplinary models in a BIM-based 3D environment, as well as visualize Revit in conjunction with Fuzor for collision detection, avoiding a number of fundamental design errors, as shown in **Figure 3**. In addition, the "Schedules/Quantities (all)" function of Autodesk Revit 2020 can be used to directly count the list of consumable engineering quantities such as interior tiles, wall tiles, and painted areas of the model room, which can be used as indirect data for later statistics of the cost of the model room, as shown in **Figure 4**.
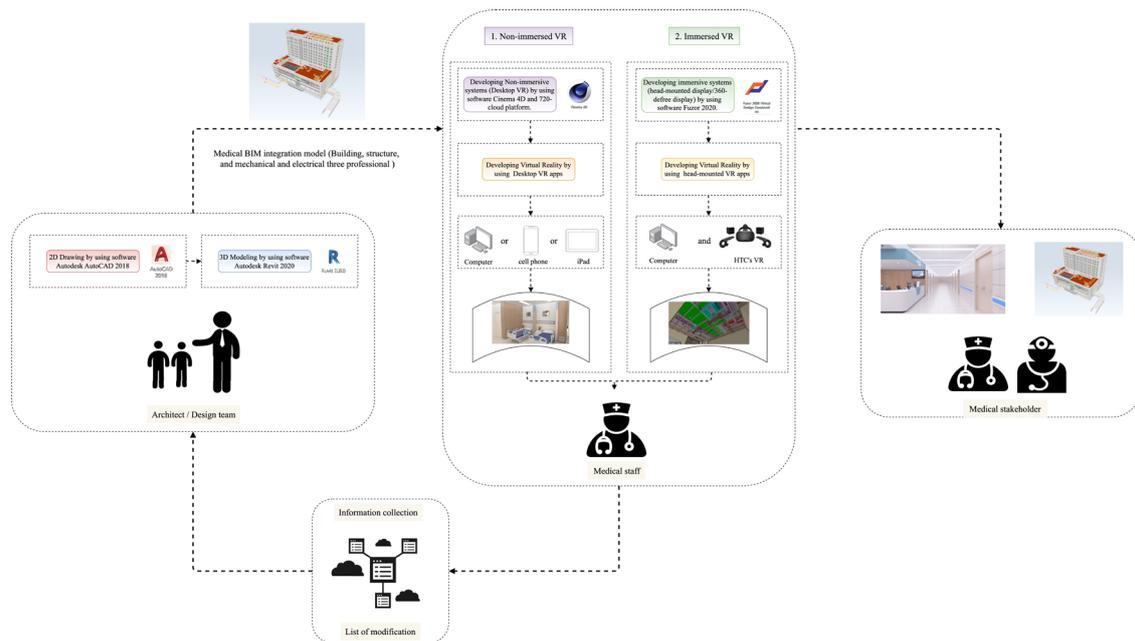
Figure 2 The structure and process for developing and designing a virtual reality application.

The second step is to export the 3D model from Autodesk Revit 2020 as an FBX file, then import the 3D model into Cinema 4D R19, and create material maps for all the models, as well as create Redshift ball cameras for several key views in the room and render the real-time output of 720° panoramic photos. Material mapping in Cinema 4D R19 is shown in **Figure 5**.

In the third step, all the panoramic photos at 720° are uploaded to the 720-cloud platform to create VR panoramic photos to achieve a non-immersive VR experience. The "walk-through" movement in non-immersive system integration is controlled via "KMS" (keyboard mouse screen) or cell phone or iPad, as shown in **Figure 6**.
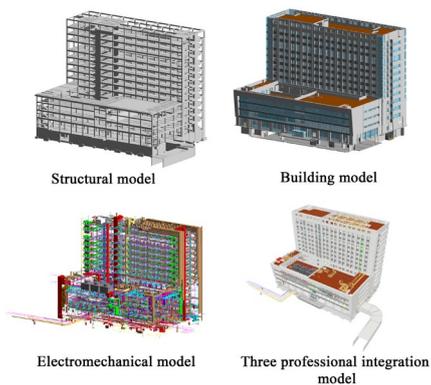
The BIM models of the case study project.

Revit + Fuzor collision detection optimized corridor.

Figure 3 The BIM models and collision detection.

Details list of ward wall tiles ✕ | Detailed list of ward wall tiles

⟨Details list of ward wall tiles⟩

A Type	B Width	C Height	D Area	E Location
Wall Tiles (2)	535.000 mm	295.000 mm	0.158 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	295.000 mm	0.174 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	295.000 mm	0.174 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	295.000 mm	0.174 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
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Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	295.000 mm	0.174 m²	Type A ward, 4th
Wall Tiles (2)	135.000 mm	585.000 mm	0.079 m²	Type A ward, 4th
Wall Tiles (2)	135.000 mm	295.000 mm	0.040 m²	Type A ward, 4th
Wall Tiles (2)	535.000 mm	585.000 mm	0.313 m²	Type A ward, 4th
Wall Tiles (2)	245.000 mm	585.000 mm	0.143 m²	Type A ward, 4th
Wall Tiles (2)	535.000 mm	585.000 mm	0.313 m²	Type A ward, 4th
Wall Tiles (2)	245.000 mm	585.000 mm	0.143 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
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Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	335.000 mm	585.000 mm	0.196 m²	Type A ward, 4th
Wall Tiles (2)	335.000 mm	585.000 mm	0.196 m²	Type A ward, 4th
Wall Tiles (2)	535.000 mm	585.000 mm	0.313 m²	Type A ward, 4th
Wall Tiles (2)	235.000 mm	585.000 mm	0.137 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	535.000 mm	585.000 mm	0.313 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	590.000 mm	585.000 mm	0.345 m²	Type A ward, 4th
Wall Tiles (2)	185.000 mm	585.000 mm	0.108 m²	Type A ward, 4th
Wall Tiles (2)	185.000 mm	585.000 mm	0.108 m²	Type A ward, 4th
Wall Tiles (2)	235.000 mm	390.000 mm	0.092 m²	Type A ward, 4th
Wall Tiles (2)	585.000 mm	585.000 mm	0.342 m²	Type A ward, 4th

Details list of ward wall tiles | Detailed list of ward wall tiles ✕

⟨Detailed list of ward wall tiles⟩

A Type	B Width	C Height	D Area	E Location
Wall Tiles (1)	35.000 mm	185.000 mm	0.006 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	185.000 mm	0.006 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	285.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	285.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	35.000 mm	290.000 mm	0.010 m²	Type A ward, 4th
Wall Tiles (1)	145.000 mm	85.000 mm	0.012 m²	Type A ward, 4th
Wall Tiles (1)	145.000 mm	85.000 mm	0.012 m²	Type A ward, 4th
Wall Tiles (1)	185.000 mm	84.977 mm	0.016 m²	Type A ward, 4th
Wall Tiles (1)	185.000 mm	84.977 mm	0.016 m²	Type A ward, 4th
Wall Tiles (1)	185.000 mm	85.000 mm	0.016 m²	Type A ward, 4th
Wall Tiles (1)	185.000 mm	85.000 mm	0.016 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	55.064 mm	0.016 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	55.064 mm	0.016 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	74.988 mm	0.022 m²	Type A ward, 4th
Wall Tiles (1)	300.000 mm	74.988 mm	0.022 m²	Type A ward, 4th
Wall Tiles (1)	245.000 mm	95.000 mm	0.023 m²	Type A ward, 4th
Wall Tiles (1)	245.000 mm	95.000 mm	0.023 m²	Type A ward, 4th
Wall Tiles (1)	285.000 mm	85.000 mm	0.024 m²	Type A ward, 4th
Wall Tiles (1)	285.000 mm	85.000 mm	0.024 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	85.000 mm	0.025 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	85.000 mm	0.025 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	85.000 mm	0.025 m²	Type A ward, 4th
Wall Tiles (1)	135.000 mm	190.000 mm	0.026 m²	Type A ward, 4th
Wall Tiles (1)	135.000 mm	190.000 mm	0.026 m²	Type A ward, 4th
Wall Tiles (1)	95.000 mm	290.000 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	95.000 mm	290.000 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	95.000 mm	295.000 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	95.000 mm	295.000 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	95.000 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	290.000 mm	95.000 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	335.000 mm	84.977 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	335.000 mm	84.977 mm	0.028 m²	Type A ward, 4th
Wall Tiles (1)	190.000 mm	185.000 mm	0.035 m²	Type A ward, 4th

Figure 4 Schedules/Quantities (all).
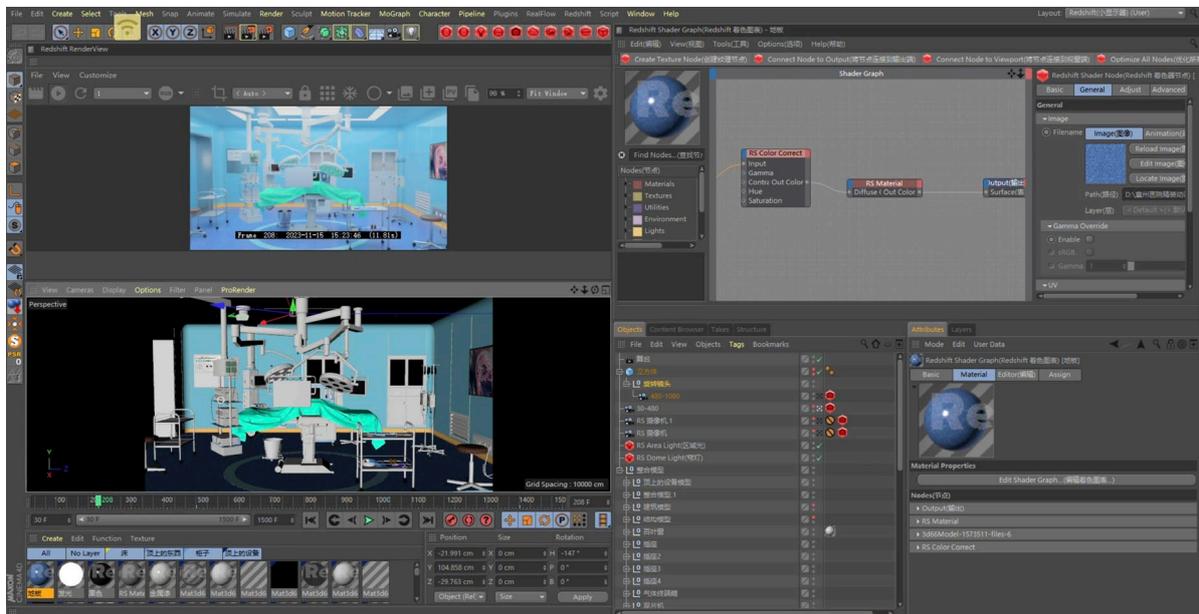
Figure 5 Conduct material mapping through Cinema 4D R19.

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Figure 6 Non-immersive VR.

Finally, the BIM model is from Autodesk Revit 2020 imported into Fuzor 2020 software, and VR mode is activated to enable an immersive VR experience using HTC's VR Head-Mounted Display (HMD) and gamepad. Navigation within the BIM model is controlled using the handles in both hands, and detailed information about the components of the BIM model can be viewed and examined, as shown in **Figure 7**. Fuzor stands out among its peers as it is not only software designed based on a game engine but also supports VR functions and boasts bidirectional synchronization capabilities with Revit. The Revit add-on provided by Fuzor is particularly critical, allowing users to seamlessly convert Revit models into Fuzor models. This conversion is not only convenient but

also enables efficient data synchronization: any changes made in the Revit model are automatically reflected in the Fuzor model. Furthermore, Fuzor's multi-role online collaboration mode is another significant advantage. Through this mode, all project stakeholders can join the cloud-based VR scene, choose different roles to roam freely within the model and share screens in real-time. This interactive method greatly enhances communication efficiency and facilitates collaboration and information sharing among project team members, as shown in **Figure 8**. Thus, these features of Fuzor not only improve the efficiency of the design and construction processes but also optimize project management and team collaboration.

Figure 7 Immersive VR.

5. Pilot case study

This research applied two kinds of VR applications based on the BIM model: non-immersive VR and immersive VR. Both applications are designed to facilitate communication between the design and medical teams. Let the medical staff do it; what you see is what you get.

5.1 BIM + non-immersive VR

Integrating BIM models with real-time rendering in the software Cinema 4D R19 facilitates a comprehensive comprehension of interior decoration effects in each room, guaranteeing functional utility and decorative outcomes. Concurrently, timely communication and discussions with the medical team enable visualized walkthroughs to pre-confirm the approach and effects of sample rooms, thereby avoiding subsequent modifications and laying the foundation for handover.
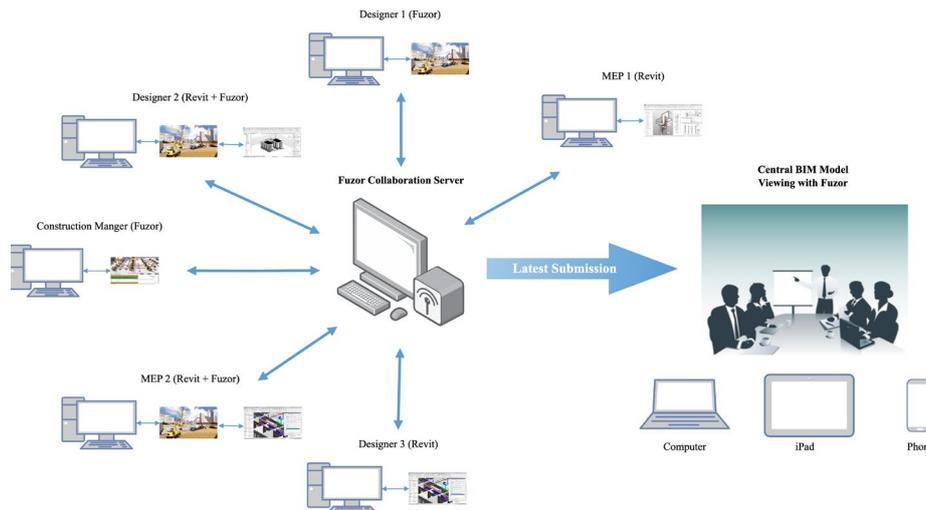
Figure 8 Fuzor's multi-role online collaboration mode (Be adapted from Fuzor 2023 User Manual [31]).

Using non-immersive VR technology, the design and medical teams can communicate more effectively in the virtual environment based on the BIM model. Even if the medical staff does not have professional knowledge of architecture, they can also find unreasonable places with the design team for the first time and get effective feedback right away. There is no difference between non-immersive and immersive VR technology in terms of the overall process; the difference is that medical staff do not have to wear VR glasses and controllers in a specific environment every time and can see the virtual VR environment with their naked eyes, it avoids the possibility of 3D vertigo for medical staff. It facilitates discussions between the design team and medical staff by allowing convenient electronic devices like mobile phones or iPads so that multiple people can view the VR model anytime, anywhere. Moreover, Non-immersive VR combines Cinema 4D's advanced rendering engines and is closer to the actual effect of construction projects after completion than immersive VR. In addition, in this study, the design effect can be viewed anytime and anywhere by using online links or 2D codes, significantly reducing the communication cost between the design team and the medical team and reducing the number of design changes. The virtual fine decoration room is shown in **Figure 9** (Link to the webpage of the VR fine decoration: https://www.720yun.com/t/93vk6q8eO2m).

Figure 9 BIM + non-immersive VR.

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5.2 BIM + immersive VR

Combining BIM models with Fuzor 2020 software realize immersive VR technology, designers and medical staff can be immersed in a virtual environment based on BIM templates, which allows you to walk freely in a virtual environment and view detailed information about BIM builds, facilitating more intuitive comprehension of design intricacies and spatial configurations. This interactive experience far surpasses the limitations of traditional 2D drawings, three-dimensional models, and the BIM + non-immersive VR system.

VR technology enables clients to "step into" the building before construction, presenting a considerable advantage for non-professionals by offering a more intuitive method to comprehend and evaluate designs. The fusion of BIM and VR allows all stakeholders in a project, including designers, engineers, contractors, and medical staff, to collaborate and communicate more effectively. The amalgamation of BIM and VR presents unparalleled opportunities for the architecture industry by enhancing the efficiency and convenience of design, construction, and management processes. As technology continues to advance, the application of this synergy is anticipated to become increasingly widespread and profound. The use of the BIM + immersive VR system is shown in **Figure 10**.

(**a**)
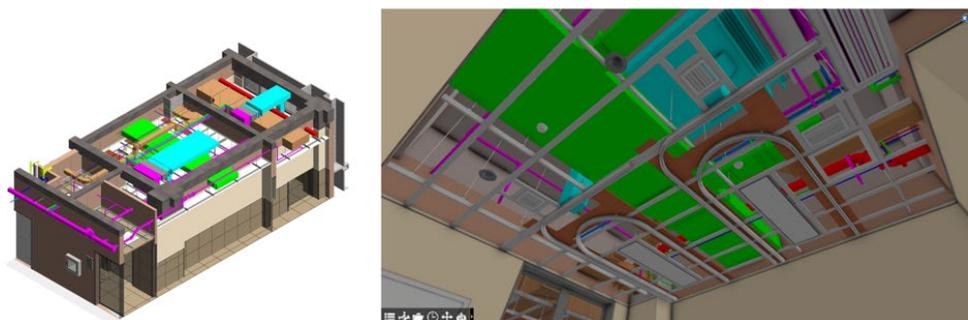
Revit model of the sickroom   Fuzor VR model of the sickroom

(**b**)

Figure 10 BIM + immersive VR (**a**) Immersive VR demo effect (**b**) Comparison of Fuzor and Revit models

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6. Discussion

This integrated BIM + VR technology system has been identified as capable of enhancing the understanding of medical staff and stakeholders regarding the design content and reducing the communication gap between these groups and the design team. To validate the effectiveness and performance of this integrated system in the design phase of MBPs, an online semi-structured interview was conducted with 16 experts (e.g., 4 designers, 4 engineers, 4 contractors, and 4 medical staff) to understand their views on the system's functionality, efficiency and stability; their satisfaction with the user interface; and their willingness to use this system for communication during the design phase.

The development of this integrated system took two months and involved four engineers. Two BIM engineers developed the related BIM models, while two system engineers were responsible for designing, developing, and testing the system. The total cost of the case study was 111,700 RMB; see **Table 1** for details. Moreover, this study compares and analyzes four different communication methods, namely, 2D CAD, 3D Models, BIM + Non-Immersive VR, and BIM + Immersive VR, as shown in **Table 2**.

Table 1 The total cost of the case study

Detailed content	Cost (RMB)
The wages of four engineers	64000
HTC's VR HMD	1700
One-year usage rights of Autodesk Revit 2018 and Fuzor 2020	11000
Two HP workstations equipped with i9-9900K processors and RTX 2080Ti graphics cards	35000
Total	111700

The results of the semi-structured interviews show that the overall average satisfaction of the engineers is 97.20%, the designers are 96.80%, and both the contractors and the medical staff are 96.40%. These data indicate a high level of user willingness and satisfaction with the system, particularly among the engineers and designers. In terms of satisfaction with system usage, the average satisfaction scores for the designers, contractors, and medical staff are the highest, reaching 4.83 points, while the engineers are slightly lower at 4.75 points. Regarding satisfaction with the system's capability and willingness to communicate through the system, the engineers have the highest average satisfaction score of 4.89 points, followed by the designers (4.84 points), and finally, the contractors and medical staff (4.82 points). Moreover, **Table 3** provides detailed data on the system evaluation results by designers, engineers, contractors, and medical staff.

This research developed an innovative integrated system that cleverly combines BIM, advanced rendering engines, and VR technology in both semi-immersive and immersive VR environments. Case studies have shown that, compared to traditional methods, this system offers several major advantages:

- In the healthcare sector, this system provides stakeholders and medical staff with a more intuitive visual communication method, significantly enhancing the efficiency and understanding of the design process.

- Notably, by integrating BIM, rendering engines, and VR technologies, the system greatly improves visual simulation performance in the VR environment. User feedback indicates that the simulation effects are far superior to those achieved using BIM models alone.

- To address the issue of digital motion sickness in VR environments, the research adopts a dual approach of both semi-immersive and immersive methods for

system design and development.

- This system not only provides clearer visualization of design outcomes but also inspires medical staff to propose more constructive requirements, especially encouraging their active participation in discussions about healthcare design.

- With its 360-degree panoramic capability, all participants can access design outcomes comprehensively through panoramic images and

interactive virtual views, thereby achieving a deep understanding and evaluation of the design.

- Normally immersive VR simulated the user on the VR headset in which user will not see

- any real surround environment, whereas non-immersive VR can see the VR on the screen with real

- environment as background behind. Both can walk-through the 3D environment

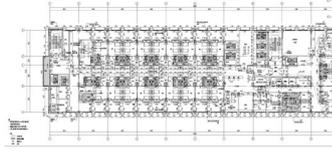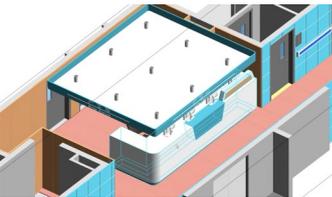**Table 2** Comparison results of previous communication tools.

2D CAD Drawing of 1:50		The design team often presents design outcomes to clients using two-dimensional drawings. With 2D drawings, it is challenging to explain and clarify complex design results. Furthermore, medical staff who have no knowledge of the AEC find it difficult to express their design requirements, suggestions, and feedback using 2D drawings.
3D Models of Revit		Compared to two-dimensional drawings, three-dimensional models offer clients a more intuitive understanding of design, enhancing the comprehension of design outcomes and the accuracy of workload estimation for construction projects. However, developing these models is time-consuming and resource-intensive, and there are still technical limitations in their expression, which may affect the effectiveness of the presentation.
The BIM+VR Integrated System — **BIM+ Non-Immersive VR**		Applying non-immersive VR technology in the MBPs design stage has significantly improved communication efficiency. This technology enables users to understand the interior decoration of medical buildings more intuitively and conveniently. Professionals can easily view design plans through mobile electronic devices, facilitating communication and collaboration and efficiently identifying and solving problems. Moreover, it enhances work efficiency and the quality of design and construction decisions.
The BIM+VR Integrated System — **BIM+ Immersive VR**		The integrated system offers a VR interactive environment; it also supports modified 3D models that are updated in real-time in a VR environment. where medical staff can freely walk in the virtual environment and interact with the design models created by MBPs. This enables medical staff to be inspired or to promptly identify any design flaws, allowing them to provide design requirements and modifications to the design team in a more timely and clearer manner. Moreover, it enhances work efficiency and the quality of design and construction decisions.

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Table 3 Engineers, Designers, Contractors, and Medical staff's system evaluation outcomes.

System Usage	Mean			
	Engineers	Designers	Contractors	Medical staff
Facilitation of efficient communication.	5	5	5	5
User-facing interface.	4.5	4.75	5	5
Willingness to talk to each other through the system.	4.75	4.75	4.5	4.5
Average Satisfaction of System Usage	4.75	4.83	4.83	4.83
System Capability	Engineers	Designers	Contractors	Medical staff
Improve the knowledge gap on design outcomes.	5	5	5	5
Clearly illustrates the requirement.	5	4.25	4.25	4.25
Comprehends the design result with clarity.	5	4.75	5	5
Delivers a VR/BIM demonstration within a VR environment.	5	5	4.75	4.75
Makes it easier to look around in a virtual world.	5	5	5	5
Effectively improves the find-path functionality.	4.75	5	4.75	4.75
Effectively improves the usefulness of the sign.	5	4.75	5	5
Effectively enhances the panoramic surroundings.	5	4.75	5	5
Effectively enhances the illustration of visual design.	4.25	5	4.75	4.75
Enhances the display to meet the needs of the users.	4.75	4.75	4.5	4.5
Effectively enhances the performance of design inspection.	5	5	5	5
Average Satisfaction of System Capability	4.89	4.84	4.82	4.82
Overall Satisfaction	4.86	4.84	4.82	4.82
Overall Average Satisfaction	97.20%	96.80%	96.40%	96.40%

Note: The mean is determined by analyzing the responses provided by participants on a five-point Likert scale. (Adapted from Lin et al. [14]).

7. Conclusion

Compared to traditional methods (2D drawings and standalone BIM models), this VR-integrated system demonstrates significant advantages in the field of healthcare design. It not only improves communication efficiency between the design team and healthcare stakeholders but also greatly enhances visual interaction by integrating VR and BIM technologies. This system, in both semi-immersive and immersive VR environments, streamlines the decision-making process and increases the precision and efficiency of design.

Additionally, it effectively stimulates medical staff to propose more constructive demands and encourages their active participation in healthcare design discussions. Based on the results of the semi-structured interview, engineers have given the system an overall high satisfaction rating of 97.20%. This reflects the system's high effectiveness and popularity in practical applications among engineers. Additionally, regarding satisfaction with system usage, the average satisfaction scores for designers, contractors, and medical staff are notably high, reaching 4.83 points. Furthermore, in terms

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of satisfaction with the system's capability and the willingness to communicate through the system, engineers reported the highest average satisfaction score of 4.89 points. These data indicate a high level of user willingness and satisfaction with the system, particularly among the engineers and designers. Based on the results of case studies, it is evident that the system, which integrates BIM, advanced rendering engines, and VR technologies, is an extremely effective visual communication tool in the design of medical construction projects.

In this case study, three primary limitations have been identified, which may impact the practical application of the integrated system.

- Firstly, the initial investment in software and hardware presents a significant implementation barrier. Due to high costs, many design teams (such as architects) or project owners are often reluctant to invest substantially in adopting VR/BIM communication technologies without explicit support from top management.

- Secondly, to meet the specific requirements of medical personnel, design teams may need to spend additional time making multiple revisions to the BIM models. These modifications need to be synchronized with both non-immersive and immersive VR systems, increasing the time cost of the project.

- Lastly, creating and modifying all BIM models according to different needs requires a considerable amount of time. Therefore, under time constraints, the creation and modification of BIM models in practical implementation may not fully meet expectations. These limitations highlight the practical challenges that need to be considered in the promotion and implementation of such integrated systems.

Future research should prioritize exploring the potential of integrating artificial intelligence technology with BIM and VR, especially in medical construction projects. AI-based BIM+VR technology can automate the identification of detailed three-dimensional information about medical spaces and the usage requirements of medical personnel, thereby creating corresponding VR environments. This significantly reduces the need for designers to repetitively modify BIM models in response to medical personnel's requests and saves valuable design time. Moreover, the application of this technology in an interactive BIM + VR environment can be extended to efficient management of hospital facilities and disaster prevention planning. Exploring this research direction will help enhance the efficiency and quality of medical architectural design and management, bringing broader innovative applications to medical construction projects.

8. Acknowledgment

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