Design and Evaluation of Virtual Reality Application for Building Information Modelling

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Yu QingDong[1], Norziha Megat Mohd Zainuddin[2*], Doris Wong Hooi Ten[3], Yang LingLing[4], Nurazean Maarop[5], Hazlifah Mohd Rusli[6], Xinyue Lu[7]

[1,2,3,4,5,6] Faculty of Artificial Intelligence,
Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia

[7]School of Civil Engineering,
The University of Queensland, 78, St Lucia Qld 4067 Australia

Emails: yuqingdong@graduate.utm.my[1], norziha.kl@utm.my[2*], doriswong@utm.my[3], yanglingling@graduate.utm.my[4], nurazean.kl@utm.my[5], hazlifah@utm.my[6], xinyue.lu1@uq.edu.au[7]

*Corresponding author
norziha.kl@utm.my

Abstract

In the realm of architectural design and construction, the integration of Virtual Reality (VR) with Building Information Modelling (BIM) presents a transformative approach to overcome the inherent limitations of traditional two-dimensional models. This research focuses on enhancing the interactivity and user engagement in BIM through VR technology, offering a dynamic and immersive experience that transcends the spatial constraints of two-dimensional models. Central to these endeavors is the development of a VR application designed specifically for university environments, aiming to augment BIM processes with intuitive functionalities like advanced roaming navigation, district-specific exploration, selective layered displays, and comprehensive measurement tools. By employing the structured Waterfall lifecycle methodology, the project ensures a systematic progression through stages of planning, design, implementation, and testing. The findings from the seven experts who evaluated six aspects of application performance show an average value of 89 percent. This indicates a reasonably excellent degree of user experience. Additionally, the item content validity index shows a value of 0.89, which is considered acceptable. End-user testing, which involved 20 respondents from public university in Hong Kong, received good feedback, mostly above average, and is considered to meet the high standards of usability. Hopefully, this research will bridge the gap between traditional BIM and VR, enhancing educational and professional experiences in universities.

Keywords: *Virtual Reality; Building Information Modelling; Immersive Experience; User Engagement; System Design; Functional Testing; Experts Evaluations; End-User Testing*

1. Introduction

Building Information Modelling (BIM) has emerged as a transformative technology in architecture and construction management, revolutionizing how digital representations of buildings and infrastructure are created and managed. BIM facilitates the development of highly detailed, three-dimensional (3D) digital models, enabling more efficient planning, design, construction, and facility management throughout the building lifecycle [1]. Despite its advantages,

* *Corresponding author. norziha.kl@utm.my*

traditional BIM approaches often remain constrained by two-dimensional visualization methods, limiting user interaction and spatial understanding, especially when dealing with intricate architectural designs [2]. To address these limitations, integrating Virtual Reality (VR) with BIM offers a more immersive, interactive experience, transforming static digital models into dynamic environments where users can navigate and explore architectural spaces as if they were physically present.

Recent market trends reflect growing interest in VR technologies, with the International Data Corporation (IDC) projecting a compound annual growth rate of 32.6% for VR headset shipments from 2023 to 2027, indicating a rising demand for more interactive digital experiences in various sectors, including architecture and construction [3]. Leveraging these advancements, VR can significantly enhance BIM by providing users with a fully immersive environment that allows for real-time interaction with architectural models. This integration enables architects, engineers, and educators to better understand spatial relationships, material textures, and lighting effects, improving design accuracy and collaborative processes [4].

However, the application of VR in BIM has often been limited to passive visualization, lacking the dynamic interaction needed for comprehensive architectural analysis. Traditional BIM systems have been designed more for information management rather than immersive engagement, resulting in a gap between the potential and actual utilization of VR in architectural modelling [5]. This gap is particularly evident in educational settings, where current methods of combining BIM and VR have produced fragmented experiences that do not fully exploit VR's capabilities. For instance, while models may appear visually impressive, they often fall short in providing interactive engagement with BIM data, such as the ability to explore layered displays or perform precise measurements within a virtual environment [6].

To bridge this gap, this research focuses on developing and evaluation, a VR-enhanced BIM application tailored for educational use public university in Hong Kong. By employing VR technology, this study aims to transform architectural visualization and interaction, providing an advanced platform for exploring digital models with greater spatial comprehension and engagement. The application leverages VR's capabilities for sophisticated navigation, district-specific exploration, and enhanced interactivity, enabling users to interact dynamically with architectural models rather than just observe them [7]. It provides an operational framework for incorporating immersive technologies into architectural modelling, responding to the increasing demand for more interactive and intuitive tools in architecture and construction [8]. The findings from this study are expected to contribute significantly to both scholarly knowledge and practical applications, setting new benchmarks for the use of VR in architectural design, education, and construction management.

2. Literature Review

The upcoming subsections explore various aspects of how advanced technologies, particularly BIM, have transformed architectural design and construction practices. The role of three-dimensional modeling is examined, highlighting its importance in visualizing complex structures and preserving cultural heritage. Additionally, the integration of BIM with cutting-edge technologies like VR offers more immersive design experiences and enhances stakeholder collaboration. Technological advancements in BIM have further streamlined project management and optimized workflows. Lastly, user-centered evaluation and performance optimization of VR-BIM applications are discussed, underscoring the significance of usability and system performance in enhancing user engagement and improving outcomes.

2.1 Building Information Modelling

Building Information Modelling (BIM) is a digital process that involves creating and managing representations of the physical and functional characteristics of places. It has transformed architectural design by providing tools for designing, constructing, and operating buildings and infrastructure more efficiently. BIM has improved project efficiency, accuracy, and sustainability by facilitating better collaboration and decision-making throughout the project lifecycle [9]. Historically, BIM has been utilized for various purposes, including restoring ancient architecture, improving construction management, and enhancing project efficiency. For instance, Liu et al. discuss BIM's utility in preserving ancient structures, while Kim and Seo focus on integrating BIM with IT convergence technologies in construction management [10] [11]. Furthermore, Xia et al. emphasize BIM's growing informatization and integration with the Internet of Things (IoT) for intelligent construction practices in China [12]. The evolution of BIM reflects its expanding role in various domains, from sustainable design to data integration and construction management, contributing to more informed and efficient construction practices [13].

2.2 Role of Three-Dimensional Modelling in Architectural Design

Three-dimensional (3D) modeling has become a cornerstone of modern architectural design, offering enhanced visualization, cultural preservation, and artistic expression. The creation of 3D models facilitates the preservation of architectural heritage by providing detailed digital representations of traditional and historic structures [14]. These models improve accessibility to architectural information and broaden its audience reach. However, challenges remain, such as the need for better-structured models that are usable outside their original design applications [15]. Advanced 3D modeling techniques also enable the seamless integration of design and art, allowing architects to visualize their work more comprehensively. For example, combining architectural modeling with artistic rendering effects allows for a more holistic and integrated approach to design [16]. Therefore, 3D modeling thus plays a vital role in modern architectural practices, helping professionals and students alike to visualize and interact with complex structures in more meaningful ways.

2.3 Technological Advancements in BIM Integration

Technological advancements in BIM have significantly impacted project management in construction, leading to more streamlined workflows and improved project outcomes Wicaksono et al. explored the use of BIM for time monitoring and control in project management, highlighting a shift from conventional software like AutoCAD to more integrated BIM systems that facilitate better cross-disciplinary collaboration [17]. Another study by Hire, S., Sandbhor, S., and Ruikar, K. demonstrates the efficacy of BIM in handling large-scale architectural projects, managing complex data, and ensuring precise project execution [18]. Tregubova and Kazaryan further emphasize BIM's effectiveness as a tool for construction organization, particularly in security planning and management [19]. These technological developments showcase BIM's versatility in addressing various project needs, from sustainability and efficiency to security and compliance, making it an indispensable tool in contemporary construction methodologies.

2.4 Integration of Virtual Reality with BIM

The integration of BIM with VR marks a significant advancement in architectural practices, offering more immersive and dynamic perspectives of building structures. This integration facilitates a comprehensive understanding of architectural projects, streamlines design processes, and enhances user engagement [20]. According to Dianwen Zhang and Fengdong An, VR based on BIM allows for dynamic management of engineering data, improving construction efficiency and enabling more effective collaboration among stakeholders [21]. The application of VR in conjunction with BIM is not limited to visualization; it extends to simulating construction scenes, supporting participatory design, and providing interactive environments for public engagement [22]. By enabling architects and stakeholders to explore design alternatives in a more intuitive and interactive manner, VR enhances the ability to make informed decisions throughout the design and construction phases.

2.5 User-Centered Evaluation and Performance Optimization in VR-BIM Applications

The success of VR-BIM applications depends heavily on user-centered evaluation techniques and performance optimization strategies. Recent studies have identified key attributes of VR, such as usability, interactivity, and visual fidelity, that are crucial for enhancing user experience and system performance [23]. User-centered evaluation methods, such as those employed by Pierdicca et al. and Pribeanu et al., ensure that VR applications align with users' needs and expectations [24] [25]. These studies demonstrate how user feedback can drive the development of more effective VR tools and methodologies, improving spatial comprehension, user engagement, and educational outcomes. Furthermore, performance optimization is essential for maintaining immersion and ensuring smooth operation in VR applications. Previous research by Hosny and Nusrat discusses various strategies for optimizing VR performance, from enhancing draw call threads to implementing more efficient rendering techniques [26] [27]. These studies contribute valuable insights into overcoming hardware limitations and optimizing VR applications to deliver more immersive and responsive experiences in architectural design and construction.

3.0 Methodology

The operational framework of this study, illustrated in Figure 1, outlines a methodical process that begins with planning and continues through development, testing, and reporting. Each phase is carefully designed to ensure the VR application meets the desired functionality and user experience goals, specifically for use in an academic environment like a university. The Waterfall methodology Figure 2 is employed to maintain a clear requirement and objectives, sequential flow of tasks, ensuring that each step builds on the previous one and suitable for large projects [28].

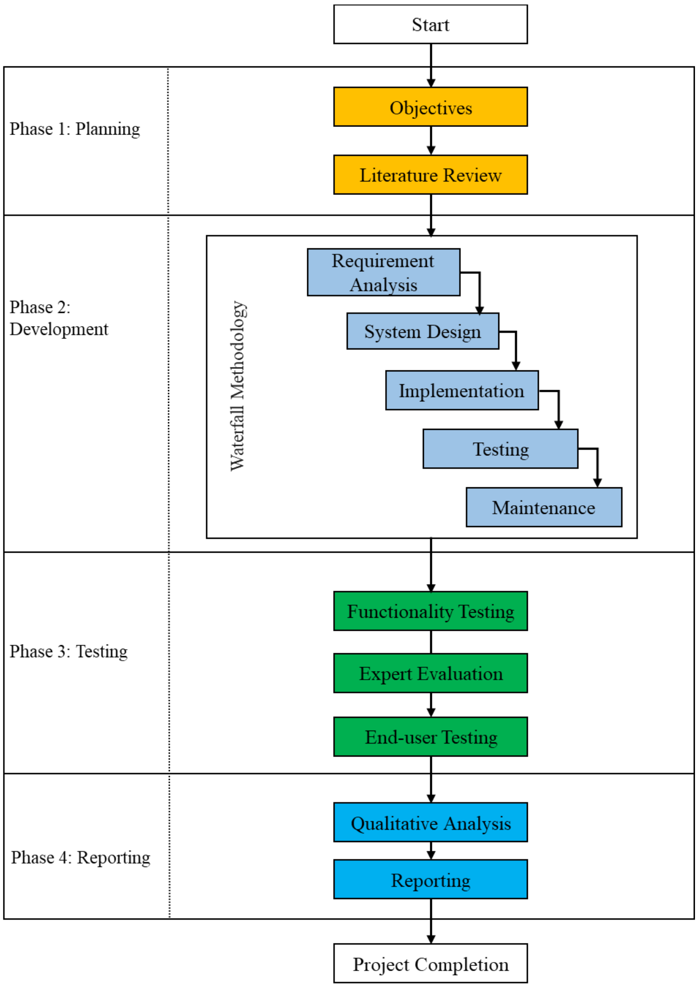

Figure 1. Operational Framework

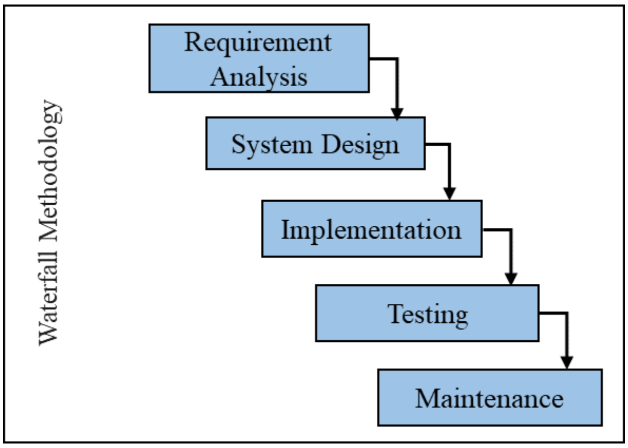

Figure 2. Waterfall Methodology [29]

3.1 Phase 1: Planning

The planning phase establishes the foundation for the entire research endeavor by defining the research objectives and conducting a comprehensive literature review. The main objective is to develop a VR application that enhances the visualization of building structures, specifically targeting the Administration Building for the public university in Hong Kong. The features of the VR application must align with the educational and functional needs of its users. Key features such as user-directed navigation, an interactive homepage, and tools for exploring layered displays and measurements are designed to provide a robust and immersive user experience.

The literature review during this phase provides a critical analysis of prior research on VR technology and interactive three-dimensional modeling, focusing on performance optimization, tools for interactive design, and simulation of structural aspects. This review helps identify the areas that require innovation, ensuring that the development process builds upon established approaches and avoids duplication of effort. This methodical approach ensures that the planning phase is aligned with the project's objectives and sets a clear trajectory for subsequent phases.

3.2 Phase 2: Development

The development phase is where the operational framework is translated into a intangible VR application. This phase follows the systematic stages of the Waterfall methodology, progressing from requirements analysis to system design, implementation, and testing.

3.2.1 Requirements Analysis

The requirements analysis phase as shown in Figure3 involves specifying both functional and non-functional requirements for the VR application to ensure a user-friendly and immersive experience. In the functional requirements define the core functionalities, such as login, home navigation, roaming navigation, district-specific displays, layered displays, and measurement tools. These functionalities enable users to interact effectively with the 3D model of the university's administrative center, enhancing both educational and professional applications.

Non-functional requirements focus on the application's performance attributes, including usability, interactivity, visual fidelity, efficiency, tracking, navigation, and instructions. These requirements ensure the VR application operates smoothly, provides a realistic experience, and is easy to use, catering to users with varying levels of technical proficiency.

Figure 3. Requirements Analysis

3.2.2 System Design

According to the requirements analysis, the system design phase involves creating a detailed design specification for the VR application shown in Fig 4. This includes developing data flow diagrams, design user interface prototypes, and identify interaction sequences that guide the application's development. The design prioritizes user engagement and intuitive navigation, particularly for exploring building structures and utilizing unique features such as layered displays.

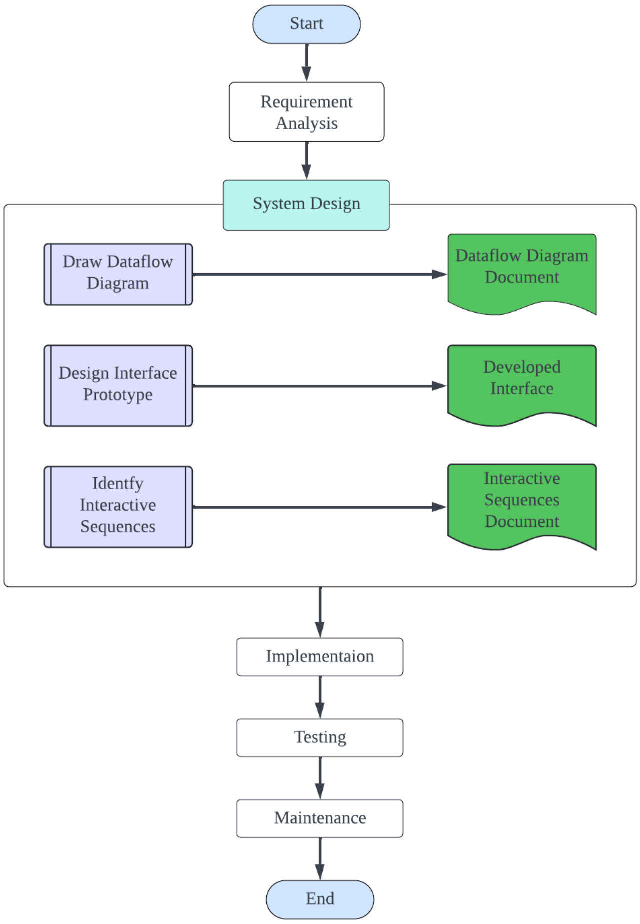

Figure 4. System Design Phase

3.2.3 Implementation

The implementation phase involves the actual coding and construction of the VR application. Developers and graphic designers collaborate to create the visual and interactive elements of the application, ensuring that each component aligns with the system design. Continuous iterative testing is performed during this phase to verify that all elements function correctly and integrate seamlessly within the VR environment.

3.3 Phase 3: Testing

The testing phase is critical for evaluating the VR application's functionality, usability, and overall user experience. This phase involves comprehensive functionality testing, seven expert evaluations, and twenty end-users testing to ensure that the application meets the desired standards and user expectations.

3.3.1 Functionality Testing

Functionality testing is conducted to verify that every feature of the VR application works as intended. Test engineers and system developers assessing the accuracy of 3D models, the realism of materials and textures, the effectiveness of lighting and visualization, and the overall user experience within the VR environment [30]. System integration tests are also performed to check for potential integration flaws among the application's components, ensuring smooth and cohesive operation. A structured rating scale in Table 1 was employed to categorize feedback from "Unacceptable" (1) to "Excellent" (5), ensuring a consistent analysis across different user groups.

Table 1. Rating Scale

Rating	Description
1	**Unacceptable**: Major issues, fails to meet basic functional or usability standards, significant improvements needed.
2	**Poor**: Frequent issues, meets very few requirements, considerable enhancements required.
3	**Average**: Meets basic requirements but has several areas for improvement to enhance efficiency and user experience.
4	**Good**: Satisfactorily meets requirements with minor issues, only slight enhancements needed.
5	**Excellent**: Exceeds requirements, no improvements needed, provides an exceptional user experience.

3.3.2 Expert Evaluations

Expert evaluations are conducted using heuristic principles to identify usability issues and ensure the VR application aligns with established usability standards [31]. This step is crucial for refining the application and addressing potential user interface issues before end-user testing. Experts are chosen based on their professional experience, familiarity with usability heuristics, and ability to provide detailed, constructive feedback. The expert evaluation of our VR application involved seven selected experts with extensive backgrounds in UX/UI design, VR development, HCI research, and software quality engineering. Their diverse expertise ensured a robust assessment based on Granollers' six aspects of heuristic evaluation, covering areas like usability, interactivity, visual fidelity, and efficiency [32]. The detailed feedback, summarized in Table 2, provided insights into strengths and potential areas for improvement.

Table 2. Experts Evaluating

Expert	Occupation	Years of Experience
1	UX/UI Designer	10
2	VR Software Developer	8
3	Architectural Consultant	15
4	HCI Researcher	12
5	Software Quality Engineer	7
6	Educational Technologist	9
7	VR Content Creator	6

3.3.3 End-User Testing

End-user testing is performed using customized questionnaires designed to gather feedback on the application's usability, educational value, and overall engagement. The feedback collected from twenty end users, typically students and educators, provides valuable insights into the practical utility of the application and helps identify areas for improvement [33]. For this research user experience data, a sample of twenty persons was collected and the sample enough to generate a 95% confidence interval that predicted the proportion who would be repeat customers within plus or minus 2.5%. Table 3, show the required sample size from the population size which involved of twenty customers.

Table 3. Required Sample Size [34]

Population Size	Confidence = 95.0%				Confidence = 99.0%			
	Degree of Accuracy/Margin of Error				Degree of Accuracy/Margin of Error			
	0.05	0.035	0.025	0.01	0.05	0.035	0.025	0.01
10	10	10	10	10	10	10	10	10
20	19	20	20	20	19	20	20	20
30	28	29	29	30	29	29	30	30

3.4 Phase 4: Reporting

The reporting phase consolidates which consolidates findings from earlier phases into a comprehensive report. This phase includes a functionality validation assessment, focusing on the effectiveness of a VR application's features, user engagement with 3D models, realism of textures, and the immersive quality of the environment. The heuristics evaluation involves seven experts using the Item-Level Content Validity Index (I-CVI) to assess the system. Additionally, a user experience evaluation gathers feedback to measure user satisfaction, ease of navigation, interface intuitiveness, and the emotional impact of the VR application, particularly in enhancing architectural education.

4.0 Findings

The VR Application Design section focuses on the comprehensive functionality and user interface of our VR platform, specifically designed for architectural visualization. This section details the findings from the development perspective and the evaluation of core components that make up the VR application, including the Login Page, Home Interface, Roaming Navigation, District-Specific Displays, Layered Displays, and the Measurement Tool which can been in Figure 5. Each function is designed to enhance the user experience by providing intuitive navigation, detailed visualizations, and interactive tools within a virtual environment.

Recent studies, such as the one by Sinoeurn and Panuwatwanich, demonstrate how cloud-based VR approaches have been utilized for remote design evaluations, which closely parallels the design of our platform's Home Interface and navigation features [35]. Additionally, Do and Sanhae highlight the importance of real-time spatial mapping in architectural visualization, showing how various mixed reality devices can support the spatial interaction and visualization needs of users, directly supporting our platform's Roaming Navigation and Measurement Tools [36]. Furthermore, real-time rendering technologies are transforming architectural practices by providing immersive and interactive walkthroughs that enable users to explore architectural models in real-time [37]. These features allow architects and users to better understand spatial relationships and interact with real-time design updates. Finally, the integration of virtual reality and real-time rendering technologies further improves visualization, providing a more intuitive and immersive way to engage with architectural models through Layered Displays and District-Specific Displays [38].

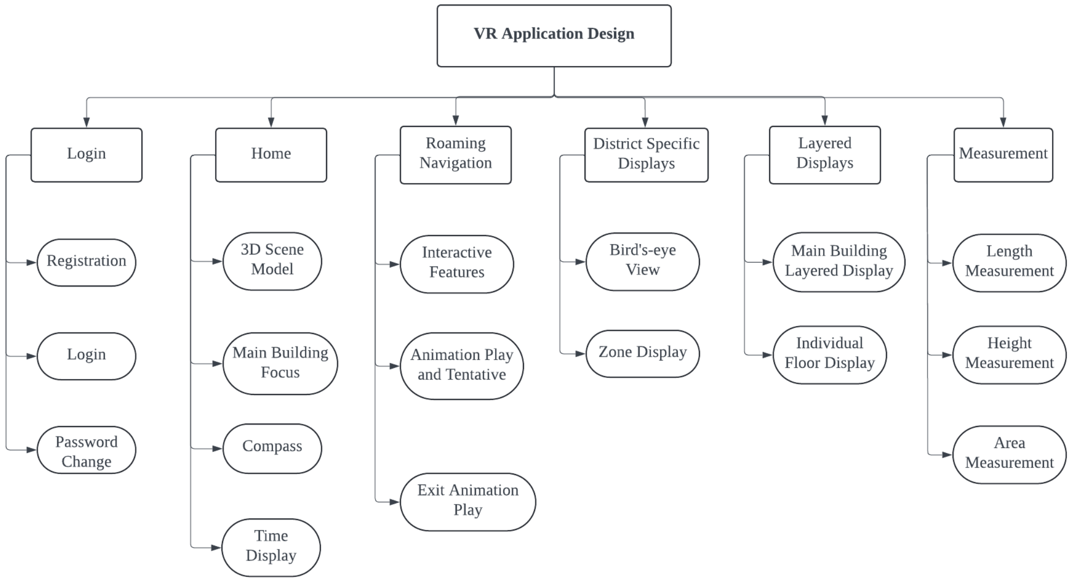

Figure 5. The Core Components and Subcomponents in the VR Application Design

4.1 Login Page

Users can access their accounts through the Login interface. This interface, as shown in the Figure 6 login interface, asks for the user's email and password. It is designed to be minimalistic yet functional, with a focus on ease of use and rapid access. The simplicity of the login form helps users quickly enter their credentials while maintaining a prominent level of security.

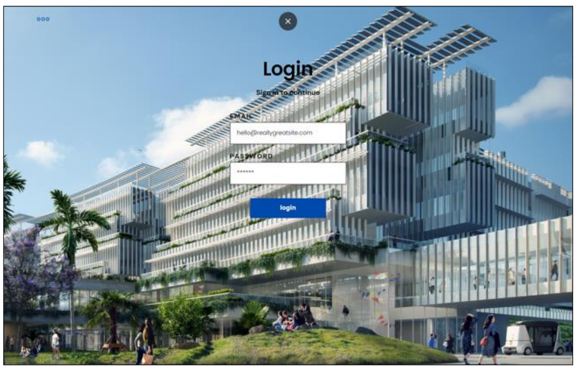

Figure 6. Login Interface

4.2 Home

The Home Figure 7 function of the VR application serves as the central hub for user interaction, providing a dynamic and immersive entry point into the virtual representation of the university environment. This function is designed to engage users immediately upon login, offering them a comprehensive and visually appealing overview of the university's 3D scene, including detailed models of main buildings.

The Home interface features a meticulously detailed 3D model of the university, which is the core of the user experience. This interface not only displays the main building but also integrates navigational aids such as a compass and a real-time clock, enhancing the user's orientation and interaction within the virtual space. At the Home interface, users are greeted with the following functionalities.

Figure 7. Home

4.2.1 3D Scene Model

The detailed 3D representation of the university allows users to visually explore the campus layout and main architectural features. This model serves as both an informational resource and a navigational tool, helping users familiarize themselves with the campus environment from a virtual perspective Figure 8 is the 3D scene model.

Figure 8. The 3D Scene Model

4.2.2 Main Building Focus

The detailed model of the main building serves as a prominent feature within the interface, offering users the opportunity to explore and interact with the core architectural structure of the campus. This specific feature allows users to gain in-depth insights into key architectural elements and the building's spatial dynamics of the main building as show in Figure 9.

Figure 9. Main Building Focus

4.2.3 Compass and Time Display

Integrated at the top of the view, the compass helps users maintain their bearings as they navigate through the virtual space. The time display adds a layer of practicality, providing real-time updates that help in planning and scheduling within the virtual environment show in Figure 10 related to compass and time display.

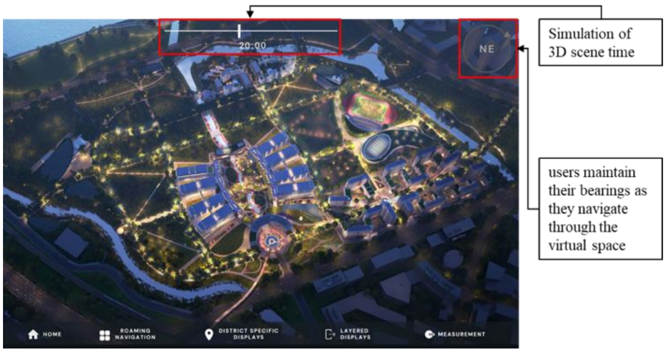

Figure 10. Compass and Time Display

4.3 Roaming Navigation

The Roaming Navigation function of the VR application is designed to enhance user engagement and interaction with the virtual environment. It is a sophisticated feature that allows users to navigate seamlessly within the 3D model of the university, offering intuitive control mechanisms for a fully immersive experience. This function incorporates three key sub-functions: Interactive Features, Animation Play and Tentative, and Exit Animation Play, each contributing to a dynamic and flexible navigation system.

4.3.1 Interactive Features

The Interactive Features of the Roaming Navigation are fundamental for a user-centered navigation experience. As illustrated, users can engage with the 3D environment through various perspective adjustments, zoom, and pan functions. These features enable users to explore the virtual campus from multiple angles and distances, enhancing the depth and quality of their interaction with the environment:

a. Perspective Changes: Allow users to alter their viewing angle, giving them a sense of spatial orientation and architectural scale.

b. Zoom: Users can zoom in to view detailed textures and architectural features or zoom out to get an overview of the campus layout.

c. Pan: This function lets users shift the viewing area across the environment, which is useful for exploring large areas without changing their virtual location.

4.3.2 Animation Play and Tentative

Animation Play adds a dynamic element to the Roaming Navigation, providing users with a pre-defined animated tour of the university. As seen in the screenshot in Figure 11 is the animation play and tentative, the feature guides users through key points of interest within the campus, offering an automated navigation option that enriches the user experience. The tentative aspect allows users to pause and resume the animation at their convenience, catering to their pace and areas of interest.

Figure 11. Animation Play and Tentative

4.3.3 Exit Animation Play

The Exit Animation Play function, shown in the screenshot Figure 12 exit animation play, gives users the ability to stop the animated tour at any point. This flexibility is crucial for user autonomy, allowing them to choose between a guided tour and independent exploration. By exiting the animation, users can explore specific areas of interest in more detail or switch back to manual navigation to satisfy their curiosity or specific information needs.

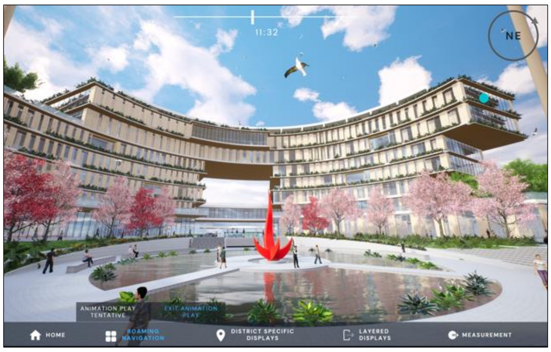

Figure 12. Exit Animation Play

4.4 District Specific Displays

The District Specific Displays function within the VR application provides an in-depth and interactive look at different zones of the university campus, facilitating user engagement with specific areas of interest. This functionality is designed to enhance the educational and exploratory experience by offering detailed views of distinct campus districts. It consists of two main sub-functions: Bird’s-eye View and Zone Display, each of which serves a unique purpose in helping users navigate and understand the campus layout.

4.4.1 Bird's-eye View

The Bird’s-eye View provides users with an aerial perspective of the entire university campus, enabling them to grasp the overall layout and relative positioning of various buildings and facilities. As illustrated in the Figure 13 bird's-eye view, this top-down view is especially useful for first-time users or those planning their visit or study at the campus, as it gives a comprehensive overview of the spatial arrangement and accessibility of the campus districts.

Figure 13. Bird's-eye View

4.4.2 Zone Display

The Zone Display feature allows users to interact with specific districts of the campus, such as the Campus Portal, Academic Research Hub, and Living Service Block. When a user clicks on a particular district within the Bird’s-eye View, the application automatically zooms in to that district, positions the area centrally, and displays related labels and detailed information [39]. This functionality, depicted in Figure 14 zone display, not only highlights the selected district but also provides contextual information that enriches the user's engagement with the area and improves user understanding.

Figure 14. Zone Display

4.5 Layered Displays

The Layered Displays function in the VR application is an advanced feature designed to provide a detailed and structured view of the university's main building, enabling users to explore architectural and spatial arrangements across different floors. This function enhances the educational and navigational experience by allowing in-depth exploration of the building's layout through an interactive and layered interface. The functionality is showcased through two primary features: Main Building Layered Display and Individual Floor Display Figure 15 main building displays.

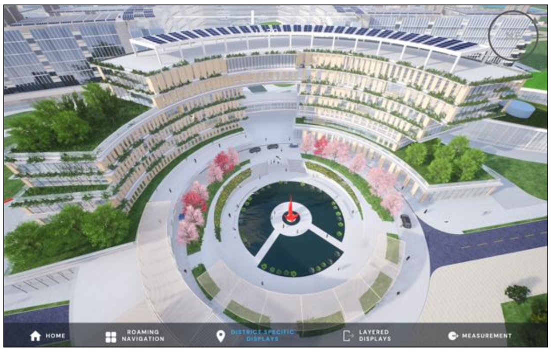

Figure 15. Main Building Displays

4.5.1 Main Building Layered Display

The Main Building Layered Display offers a comprehensive view of the entire building, allowing users to understand the overall structure and distribution of spaces within it. As depicted in Figure 16 layered displays, this feature visually separates the building into distinct layers, each corresponding to a floor or a set of floors. Users can interact with this display to peel back layers, revealing the internal layout and specific areas of each floor without the obstruction of the floors above them. This visual breakdown helps in providing clarity and aids in educational demonstrations of building architecture and facilities planning.

Figure 16. Layered Displays

4.5.2 Individual Floor Display

Clicking on a specific layer or floor in the Main Building Layered Display brings up the Individual Floor Display. This function, as shown in the screenshot Figure 17 individual floor display, focuses on a single floor, providing detailed views of the specific areas and rooms. Each area is labeled clearly, offering users information about its purpose and usage. For instance, administrative offices, lecture halls, and student service centers are individually marked, making it easy for users to locate and understand the function of each space within the building.

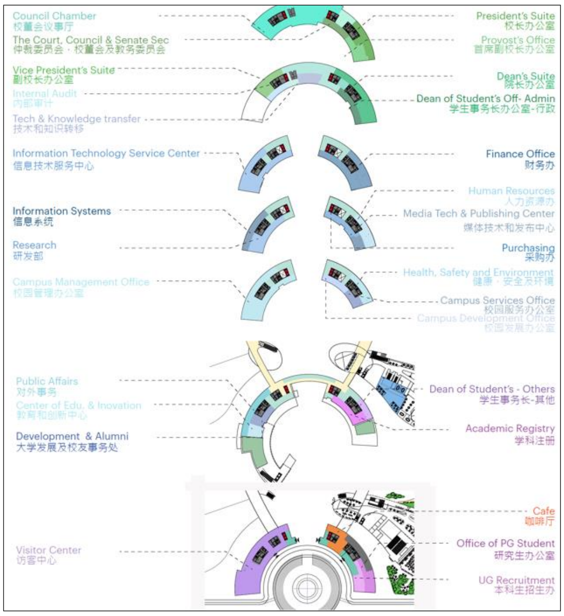

Figure 17. Individual Floor Display

4.5 Measurement Tool

The Measurement Tool in the VR application is a critical component designed to provide precise measurement capabilities within the virtual environment Figure 18 measurement tool. This feature enhances the utility of the VR application for detailed architectural and planning purposes by allowing users to measure distances, heights, and areas directly within the 3D space. The Measurement Tool is divided into three main functionalities which are Length Measurement, Height Measurement, and Area Measurement, each providing specific insights tailored to different user needs.

Figure 18. Measurement Tool

4.6.1 Length Measurement

The Length Measurement tool enables users to determine the distance between two points in the virtual environment. This feature is essential for understanding spatial relationships and dimensions within the model. Users can click on two points, and the application will display the linear distance between them, facilitating accurate planning and layout assessments. This functionality is illustrated in Figure 19 length measurement, in which a user measures the distance across a pathway.

Figure 19. Length Measurement

4.6.2 Height Measurement

Height Measurement allows users to calculate vertical distances, which is crucial for evaluating the elevation of different structures or natural features within the environment. By selecting a base point and an endpoint vertically aligned, users can obtain the height measurement, which assists in compliance with design standards and helps in creating a more realistic representation of the terrain. The Height Measurement feature is demonstrated in Figure 20.

Figure 20. Height Measurement

4.6.3 Area Measurement

Area Measurement is particularly useful for large-scale planning and land use analysis. It allows users to outline a closed area to calculate its total surface size. This tool is vital for tasks such as assessing the floor space of buildings, planning outdoor events, or landscaping projects. Users can draw a polygon around the area they wish to measure, and the application computes the enclosed area, displaying it in square meters. The functionality of this tool is depicted in Figure 21 area measurement.

Figure 21. Area Measurement

4.7 Evaluation

This section provides an overview of the evaluations conducted for the VR application, focusing on (i) functional evaluation, (ii) expert evaluation, and (iii) end-user evaluation. The evaluations employed a combination of quantitative and qualitative methods, including detailed surveys, heuristic evaluation, and usability testing.

4.7.1 Functional Evaluation

The functional evaluation tested core features like login, navigation, and measurement tools to ensure they met expected outcomes shown in Table 3. All features passed, confirming that the VR application performs as intended, providing an engaging and accurate user experience.

Table 3. Functional Evaluation

Code	Feature	Test Description	Expected Outcome	Pass/Fail
1	Login	Users need to input account and password to enter the application and can change the password.	Users can successfully enter the system when the account name and password are correct, otherwise users fail.	Pass
2	Home	Test the loading and display accuracy of the 3D model of the building.	The 3D model loads correctly and displays accurately.	Pass
3	Roaming Navigation	Evaluate ease of navigation, responsiveness of controls.	Smooth and intuitive navigation through the VR environment.	Pass
4	District Specific Displays	Test clarity and information accuracy of specific district displays.	Clear, detailed, and accurate representation of each district.	Pass
5	Layered Displays	Check functionality of layered display, including toggling between layers.	Users can easily toggle between different layers and view details.	Pass
6	Measurement Tool	Test accuracy of measurement tools in 3D space.	Measurement tools provide accurate and reliable measurements.	Pass

4.7.2 Expert Evaluation

The item used for heuristic evaluation assessed by the panel of experts are shown in Table 4. The average usability percentage derived from expert assessments is shown in Figure 22, indicating a mean score of 89%. This score suggests a high level of user experience, well above the acceptable threshold of 83% [32].

Table 4. The relevance ratings on the item scale by seven experts

No	Item	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5	Ex 6	Ex 7	Experts in agreement	I-CVI
Usability										
1	Interface Clarity: Evaluate the simplicity and clarity of the user interface. Does it facilitate an intuitive user experience?	1	1	1	1	1	1	1	7	1
2	Learning Curve: Assess the time it takes for a new user to become proficient with the application.	0	1	1	1	1	1	1	6	0.86

No	Item	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5	Ex 6	Ex 7	Experts in agreement	I-CVI
3	Consistency: Check for consistent design elements and themes throughout the application.	1	1	1	1	1	1	0	6	0.86
4	Accessibility: Determine if the application is accessible to users with varying levels of technical proficiency.	1	1	1	1	1	1	1	7	1.00
Interactivity										
5	Responsiveness: Test the responsiveness of interactive elements.	1	1	1	1	0	1	1	6	0.86
6	Realism of Interaction: Evaluate how closely virtual interactions mimic real-world interactions.	1	1	1	1	1	1	1	7	1.00
7	Feedback Mechanisms: Check the immediacy and appropriateness of feedback given to users during interactions.	1	1	1	1	1	1	1	7	1.00
Efficiency										
8	Load Times: Measure the time it takes to load the application and transition between different sections.	1	0	1	1	1	1	1	6	0.86
9	Frame Rate Stability: Monitor the consistency of frame rates during various operations.	1	1	0	1	1	1	1	6	0.86
10	Resource Management: Evaluate how efficiently the application manages system resources during high-load scenarios.	1	1	1	0	1	1	1	6	0.86
Tracking										
11	Positional Accuracy: Test the accuracy of positional tracking in the VR environment.	1	1	1	1	1	1	1	7	1.00
12	Orientation Tracking: Assess the precision of orientation tracking and its responsiveness to user movements.	1	0	1	1	1	1	1	7	0.86
13	Error Rate: Identify and measure any tracking errors or drifts that occur during use.	1	1	1	1	1	0	1	6	0.86
Navigation										
14	Tool Effectiveness: Evaluate the effectiveness and ease of use of navigation tools like teleportation and walking simulation.	1	1	1	0	1	1	0	5	0.71
15	User Orientation: Assess how well the application helps users orient themselves within the virtual environment.	1	1	0	1	1	1	1	7	1.00
16	Flexibility: Check the flexibility of navigation tools to accommodate different user preferences and scenarios.	0	1	1	1	1	1	1	6	0.86

No	Item	Ex 1	Ex 2	Ex 3	Ex 4	Ex 5	Ex 6	Ex 7	Experts in agreement	I-CVI
Instructions										
17	Clarity of Instructions: Evaluate the clarity and conciseness of onboarding tutorials and in-app help sections.	1	0	1	1	1	1	1	6	0.86
18	Accessibility of Help: Assess how easily users can access help and guidance when needed.	1	1	1	1	0	1	1	6	0.86
19	Comprehensiveness: Determine if the instructions cover all necessary aspects of the application's use effectively.	1	1	0	1	1	1	1	6	0.86
Proportion relevance		0.89	0.84	0.84	0.89	0.89	0.95	0.89	**Average I-CVI**	**0.89**
Usability Percentage (UP)		89%	84%	84%	89%	89%	95%	89%		
Average proportion of items judged as relevance across the seven experts									**0.89**	

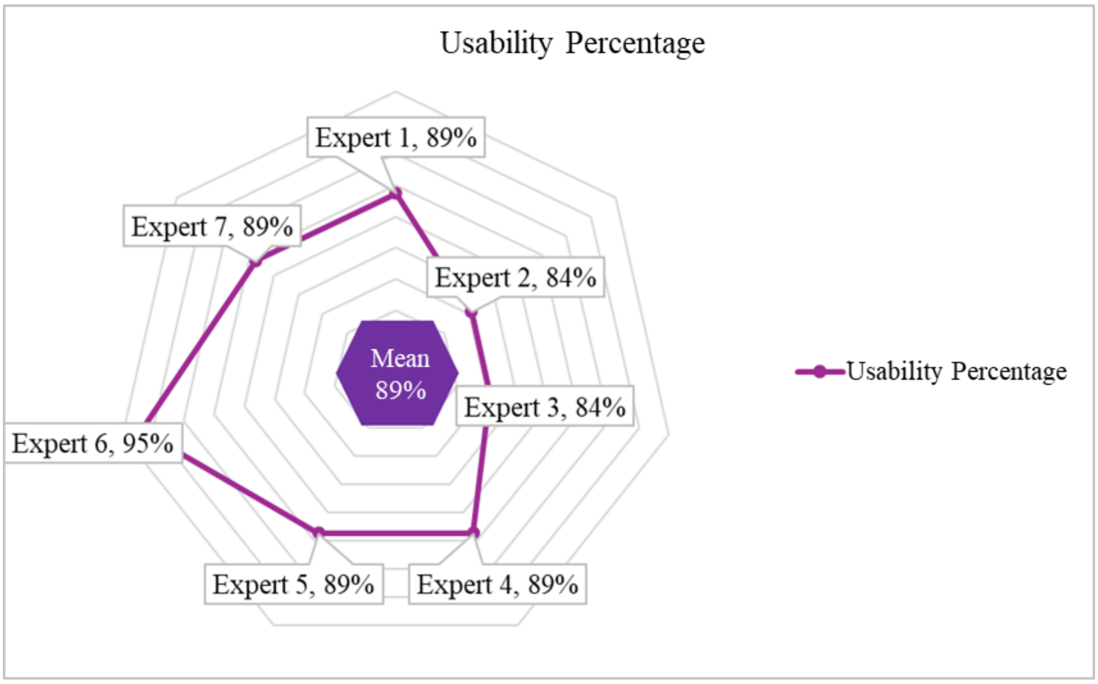

Figure 22. Usability Percentage Analysis of Heuristic Evaluation

4.7.3 End-user Evaluation

The end-user evaluation of the VR application involved 20 participants, primarily students and educators, who rated key features like the Login function, Home interface, Roaming Navigation, District Specific Displays, Layered Displays, and Measurement Tool. The feedback showed high satisfaction across all features: 85% of users rated the Login function as "Excellent," and 90% rated the Home interface, similarly, indicating intuitive and user-friendly design. Both Roaming Navigation and District Specific Displays achieved perfect scores, with 100% of users rating them "Excellent," highlighting smooth interaction and clear visual representation. Layered Displays also received a 100% "Excellent" rating for effectively displaying building layers, while Measurement Tools were rated "Excellent" by 95% of users, emphasizing accuracy and ease of use. These results, where over 85% of ratings were "Good" or "Excellent," reflect strong usability and effectiveness, aligning with established usability standards, confirming the application's success in meeting user expectations and enhancing user experience. Integrating such feedback is critical in iterative design processes to continually improve usability and user satisfaction [40].

5.0 Conclusion

This research explored the development and evaluation of a VR application for the public University in Hong Kong, designed to enhance architectural education through immersive and interactive experiences. The study demonstrated the VR application's effectiveness in improving user engagement and comprehension of architectural concepts by integrating advanced BIM with VR technology. Evaluations from experts and end-users indicated high usability, interactivity, and educational value, confirming the application's potential to transform educational practices in architecture. However, the study's limitations like a limited sample size and scope restricted to current VR technologies, suggest that further research work is needed to validate these findings across diverse user groups and settings. Future research should focus on expanding user diversity, conducting longitudinal studies to assess long-term effects, integrating VR with emerging technologies, and comparing VR platforms to enhance user experience. Addressing these areas could provide deeper insights into the utility of VR in education and beyond, ensuring that VR applications are inclusive, sustainable, and technologically advanced. Overall, this research contributes to the discourse on VR integration in learning environments, providing a foundation for future studies to build upon and further explore the potential of immersive technologies in educational and professional contexts.

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