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How Much Can VR Improve Spatial Experience? - A Case Study with a Commercial Building Project

Yi-Kai Juan[1], Hao-Yun Chi[1]*, Yang Zhang[2]

[1]Department of Architecture, National Taiwan University of Science and Technology, Taipei, Taiwan
[2]Electrical and Computer Engineering Department, University of California, Los Angeles, CA, United States

*Corresponding author's email: chihyn@gmail.com

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Abstract

With the development of Industry 4.0 and the impact of the COVID-19 epidemic, the global construction industry has undergone a rapid digital transformation, pushing the development of building information modeling (BIM), virtual reality (VR), augmented reality (AR) and mixed reality (MR) technologies towards greater maturity. However, from the perspective of building developers and end users, does VR technology have any benefit for complex building projects? What are users' acceptance and evaluation on VR emerging technology? After constructing a VR simulation navigation system for an actual commercial building project, this study investigated and compared the differences between using the VR system and the traditional navigation system in the four dimensions of the technology acceptance model. The results showed that the subjects generally believed that the VR system has significant benefits in terms of usefulness, users' attitude, and users' intention, however, there is still room for improvement in the perceived ease of use. Moreover, feedback from developers supported the benefits of the VR technology validated the system effectiveness. Hence, VR and BIM technologies are recommended to be effectively integrated, in order to enhance the integrity of industrial applications and establish a new design communication and collaboration model for the architecture, engineering, construction, and facility management industry.

Keywords: Building information modeling, virtual reality, augmented reality, mixed reality, commercial building

1.0 INTRODUCTION

The advent of the Fourth Industrial Revolution (Industry 4.0) has prompted the rapid rise of various emerging digital industrial technologies. Immersive technologies are accelerating industry changes (Ceruti et al., 2019; de Paula Ferreira et al., 2020; Roldán et al., 2019). In recent years, the applications of virtual reality (VR), augmented reality (AR), and mixed reality (MR), have gradually become the mainstream of emerging immersive technologies (Kusiak, 2018; Ratcliffe et al., 2021; Serras et al., 2020; Speicher et al., 2019). The popularity of various consumer mobile devices and the progress in software and hardware have also improved the convenience and usability of, which has pushed the comprehensive technology toward maturity (Çöltekin et al., 2020a, 2020b; McGuirt et al., 2020; Southworth et al., 2020). Many studies have shown that the application of VR technology to all stages of the building life cycle in the architecture, engineering, construction, and facility management (AEC/FM) industry has created high application values (Delgado et al., 2020; Doukianou et al., 2020; Greenwood et al., 2008; Marino et al., 2021; Sidani et al., 2021; Wen et al., 2021). Under the current threat of the COVID-19 epidemic, people are unable to have face-to-face contacts as in the past; hence, the application of VR may bring more possibilities to future works (Lee & Trimi, 2021; Lee & Yoo, 2021).

For a long time, building information modeling (BIM) technology has been the core of development of the AEC/FM industry, integrating information from different construction professions to facilitate the communication and coordination of a project (Carvalho et al., 2021; Porwal & Hewage, 2013; Ren et al., 2021; Scorpio et al., 2022; Xu et al., 2021). Nevertheless, much manual operation is required to view the model and browse the information, thus reducing the efficiency of on-site construction communication (Carvalho et al., 2021; Porwal & Hewage, 2013; Ren et al., 2021; Sidani et al., 2021). With the assistance of VR the BIM model is able to update real-time information and achieve a more intuitive and convenient real-time interaction through information visualization. This can then effectively reduce the gap in spatial cognition, improve project understandings and help in the design communication efficiency (Alizadehsalehi et al., 2020; Carrasco & Chen, 2021; Heaton et al., 2019; Kim et al., 2021; Sidani et al., 2021; Spaeth & Khali, 2018; Xu et al., 2021).

Commercial buildings are an essential component of the urban built environment. For urban environments in the narrow and densely populated regions of Asia, commercial buildings are especially important places for people to live and work. The success or failure of commercial buildings is also a critical indicator in evaluating the development of a regional economy. Property managers of commercial buildings face many business challenges from the stages of investment, design, construction, and operation. In order to enable the space of commercial buildings to meet the needs of future users and increase the competitiveness of investment promotion, information communication at the design stage is becoming even more critical. These communication contents involve preliminary design concepts, spatial scales, style presentation, equipment configuration, and various material selections (Baldwin et al., 2009; Juan et al., 2021). In the traditional architectural design process, it is often necessary to wasted large amount of paper to assist repeat the communication process to ensure design quality, which leads to a waste of workforce, time, money, and earth resources. Due to information asymmetry and cognitive differences, project disputes often arise between designers and decision makers, making it difficult to finalize decisions and therefore affecting the overall construction project performance and satisfaction (Lin et al., 2018).

In recent years, VR technologies have gradually been proven to be effective design and decision-making aids in the studies of the AEC/FM field (Alizadehsalehi et al., 2020; Juan et al., 2018; Rese et al., 2014, 2017; Schnack et al., 2021; Spaeth & Khali, 2018; Woksepp & Olofsson, 2008). However, many studies favored in applying a single technology, such as VR, AR, or MR, to explore the initial design of system development, design project cooperation, remote collaboration mode, visualization of construction methods, and improvement of service quality (Baldwin et al., 2009; El Ammari & Hammad, 2019; Juan et al., 2018; Kuliga et al., 2015; Lee & Yoo, 2021; Mourtzis et al., 2020; Niu et al., 2016). In this study, the applications of VR were interpreted as the simultaneous integration of VR into spatial experience, and as a medium for human interaction with the virtual environments.

This research, therefore, took a complex commercial building in Taiwan as a case study and introduced the development of a VR simulation navigation system for preliminary planning and design during the investment promotion stage. In order to verify the system's practicability and understand its acceptance, this study invited 30 potential investors of the development project to experience and compare the VR system with the traditional navigation system. A questionnaire based on technology acceptance model (TAM) was employed to investigate the preferences of and differences in users' attitudes, willingness to use, usefulness, and ease of use when using the two systems to validate the effectiveness of the VR system. The obtained results and implications were expected to help future building developers to introduce the VR system in their projects.

2.0 CHARACTERISTICS OF COMPLEX COMMERCIAL BUILDING PROJECTS

Commercial real estate refers to buildings that provide multi-functional services, such as offices, malls, restaurants, hotels, and leased residences, for real estate development, operation management, marketing, and investment. Commercial real estate projects are highly complex, and they can directly and indirectly attract investment from the global market and contribute to the global economy (Toivonen & Viitanen, 2015). Under the commercial real estate development model, lands and buildings have a long service life. Developers obtain long-term stable income through investment, nonetheless, they also face rapid changes in the market environment and social needs, which make project development uncertain and risky (Ullah et al., 2021).

In order to reduce development risks and enhance the competitiveness of investment promotion, developers continuously improve their project planning in all stages of building planning, design, contracting, construction, operation, maintenance, and demolition. For example, traditional developers often communicate information with future tenants during the investment promotion stage by using floor plans, construction drawings, 3D perspective drawings, and physical models (Delgado et al., 2020; Dinis et al., 2020; Sidani et al., 2021; Zhu et al., 2018). In a complex project with multiple companies and participants involved, the spatial planning and design may not satisfy all the stakeholders. In other words, from the developers' viewpoint, during the process of project implementation, the developers and stakeholders often spend too much time in reviewing graphic information and in communication. Under the circumstance of future investors having insufficient information about the project or ideas that are widely divergent from the developers, investors' willingness to invest in this project will be affected (Alizadehsalehi et al., 2020; Qiu et al., 2021).

In recent years, BIM and VR technologies have been gradually popularized. For example, Lin et al. (2018) propose BIM combined with VR for hospital building design; Kim et al. (2021) propose BIM combined with VR for the design and process evaluation of educational buildings; Scorpio et al. (2022) propose BIM combined with VR for interior lighting design of office space. The current research results focus on design, communication, and process evaluation. However, from the investor's point of view, it is relatively rare to use BIM combined with VR to implement multi-faceted application research results for the development, design, decision-making, and investment in the building lifecycle of an overall commercial building project.

The development of BIM and VR technologies in recent years can provide designers and decision-makers better decision-making assistances at the level of design information communication. Especially for large complex commercial development projects, when the building has not been constructed or has not yet been completed, BIM could be employed to strengthen the interaction between design teams and decision-makers through a common standard of the shared information and data management from an early design stage. Moreover, the VR technology can be used as an effective visualization tool to review and revise the spatial plan, which meets users' expectations in this early design stage. It is worth noting that VR technology has not been widely applied by developers, and users still have some confusion about the applicability and low acceptance of VR technologies. These are all worthy of investigation and evaluation in future research.

3.0 VR SIMULATION NAVIGATION SYSTEM DEVELOPMENT

3.1 Project Briefing

The appearance and configuration of the building are shown in Figure 2. VR simulation navigation application is a composite commercial building, as shown in Figure 1. The site is located in Taipei City and is a steel-framed building with 20 floors above ground and four floors underground. The building site area is 6,845 m^2, and the total floor area of this building is 69,766 m^2. The building will provide services to offices, hotels, and shops. The developers of this building expect that the VR technology can be developed in time for the investment promotion stage to allow potential investors to experience the spatial scale, style presentation, equipment configuration, material selection, and cost estimation in advance, so as to increase their willingness to settle there in the future.

Figure 1 Case study: Commercial building

3.1 System Development and Implementation

The study takes into account the convenience and the possibility of browsing without geographical or equipment restrictions, the VR system of this study is presented with a single-point panoramic scene. It is based on a wireless head-mounted device Samsung Gear VR paired with a handheld wireless six-axis controller. The Samsung Galaxy S9+ performs 2K image calculation and presentation, as shown in Figure 2. BIM three-dimensional architectural and interior of this project was built by Revit, Sketchup, and Rhino. Using Enscape to render a single-point surround scene in VR. The actual browsing part of VR uses 720YUN (Web VR) for node-style walking. Users can click the observation point to review the construction information (ARC, CON, MEP drawings and documents) by BIM model.

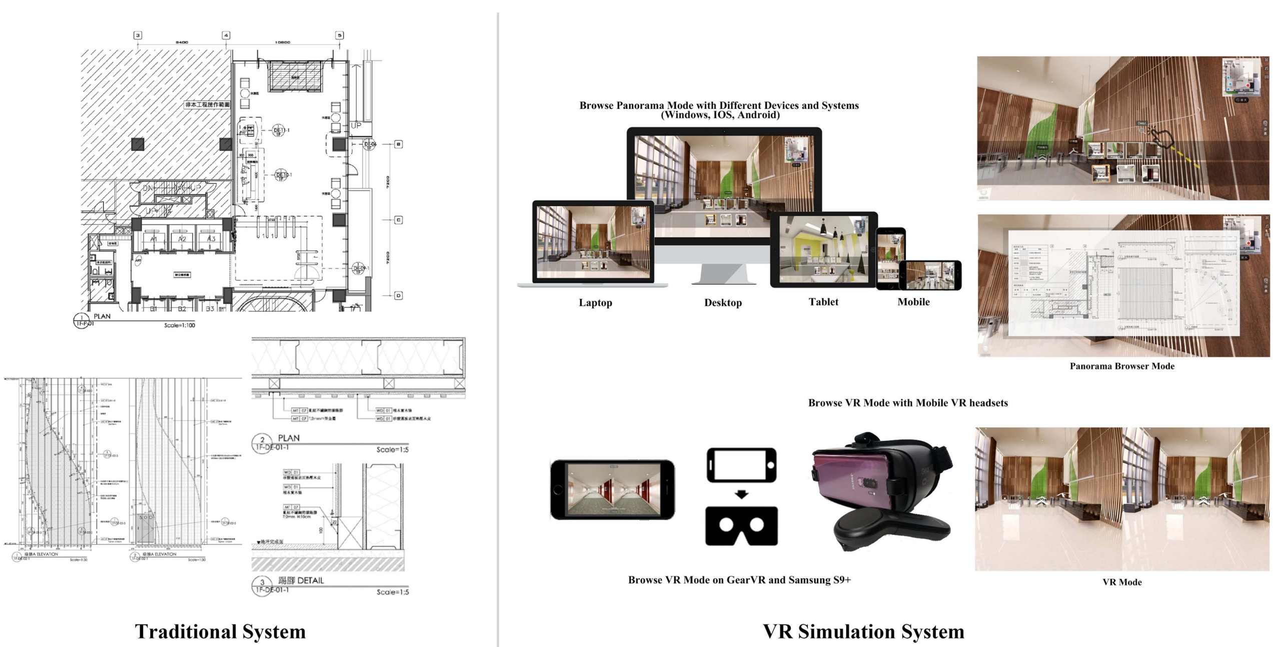
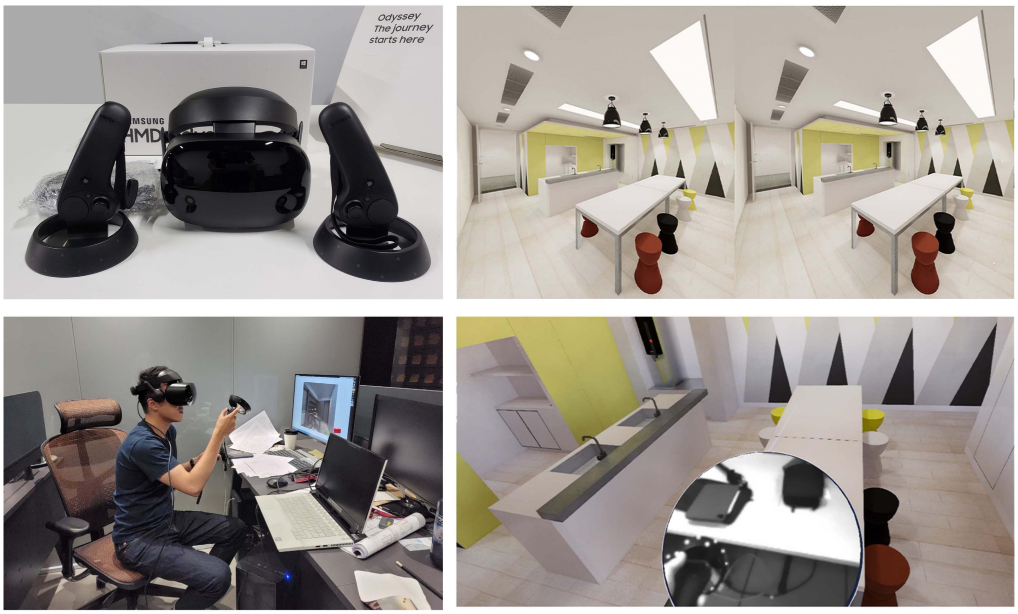


Figure 2 Compare traditional and VR simulation system demonstration

In addition to VR, we also provide MR and AR technologies to assist users in gaining a deeper understanding the commercial building project. Using the BIM 3D model we built, all information was imported into MR and AR for presentation. MR technology allows users to immerse themselves in a virtual environment, synchronize with actual locations and compare live conditions in real-time. AR technology can visualize the drawing when the user reads the physical drawing, assisting the user in understanding the surrounding environment, traffic, location, and building information of the project sooner.

The MR is based on Samsung HMD Odyssey+ Windows mixed reality headset with a wireless six-axis (degrees of freedom, DOF) MR somatosensory controller for screen calculation and presentation. The computer specification is Alienware M15R2. The processor CPU specification is I7-9750H, the graphics card GPU is NVIDIA RTX2080 Max-Q 8G, and RAM is 16G, for computer real-time rendering image transmission and image calculation and presentation. Enscape was adopted for real-time rendering of scenes that allow users to take a guided tour of the project and experience the overall spatial scale, layout, and texture. The MR uses the flashlight function of Samsung Odyssey+ Real-time comparison of the external environment in a virtual environment, as shown in Figure 3. The scene includes the indoor, outdoor, and surrounding local environment of the project.



Participant experiences in the commercial building's reception area

Interact with the real environment demonstration

Figure 3 Samsung HMD Odyssey+ Windows MR headset equipped with a handheld wireless six-axis MR somatosensory controller

AR is based on Apple iPad Pro 12.9 with an optical radar scanner for environmental scanning and image calculation, as shown in Figure 4. Next, 3D architectural and interior design models were developed by using Revit and Sketchup, and AR practical operations were performed to present the simulation of the BIM model, allowing users to navigate the building of this project Information from the BIM model, which includes details such as building overview, construction cost, building coverage rate, floor area rate, overall surrounding environments, experience the volume of the building, and provide users with a more efficient understanding of the project. This can improve the user's visual interaction experience.

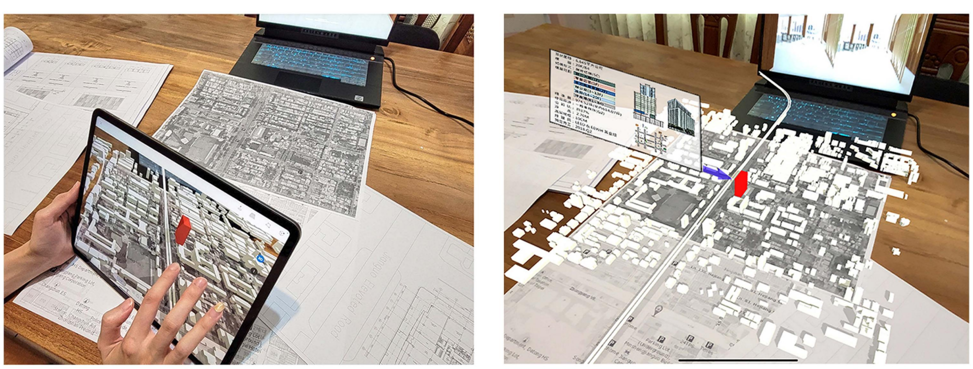


Figure 4 iPad Pro AR support navigation demonstration

4.0 EXPERIMENTAL DESIGN AND HYPOTHESES

4.1 Experimental Design

In order to verify the effectiveness of the VR simulation system and the user's acceptance of VR operations, this study invited 30 potential investors to participate in the experiment. Among the 30 subjects, eighteen are males, and twelve are women. Their age is between 30-60 years old. Their work is mainly in the middle and senior management positions of real estate investment and leasing. Furthermore, all of them have more than ten years of experience in using computers, and about 70% of the subjects have experience in VR technology. However, none of them have experience in using an VR system to conduct architectural project navigation.

The experiment was divided into a pre-test (mainly based on the traditional navigation system: interpretive experience of architectural illustrations and physical building models) and a post-test (mainly based on the VR navigation simulation system). Participants were first provided with the traditional project guide and introduction from the researcher, which lasted about 30 minutes. In order to avoid the knowledge overlap and experimental fatigue, the participants were invited to perform the experimental operation of the VR simulation system 14 days after the first experiment. The research methodology workflow, as shown Figure 5.

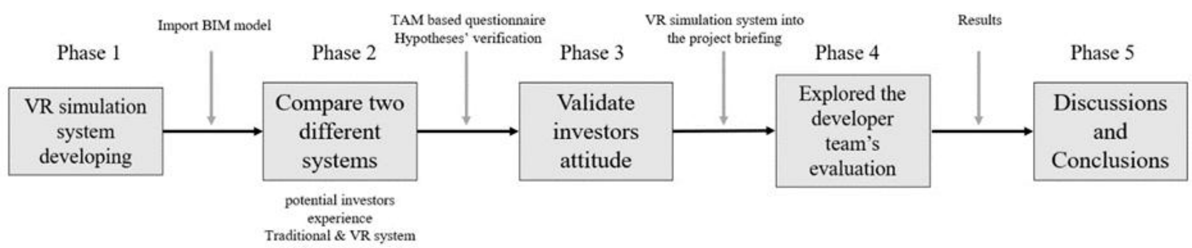


Figure 5 Research methodology workflow

4.2 Research Hypotheses

At the end of the pre- and post-test, the researcher asked the subjects to fill out a TAM-based questionnaire. TAM, an information systems theory that models how users come to accept and use a technology, was developed by Davis et al. (1989). Its purpose is to find an effective behavior pattern to explain the behaviors and attitudes of users towards a technology when accepting new information systems. This model provides a theoretical basis for understanding the influence of external factors on users' internal beliefs, attitudes, and intentions, thereby affecting their use of technology. It is also considered universally applicable to explain or predict the influencing factors for the use of information technology.

TAM indicates that perceived usefulness and ease of use affect the attitude of using technology, which in turn affects specific behaviors. It also addresses that people's use of information technology is affected by their behavioral intentions. In order to verify the practicability of the VR simulation system, this study invited 30 potential investors to participate in the research to identify the preferences and differences of the four dimensions of TAM when using different navigation systems. The four dimensions are defined as follows.

1. Perceived usefulness: It refers to the degree to which users believe that using a particular system will enhance their work performance or save effort; that is, individuals' subjective perception of using a specific information system will increase their work effectiveness.
2. Perceived ease of use: It refers to the degree to which users perceive technology to be easy to use. As the system becomes easier to use, users will have more confidence in self-efficacy and self-control, and their attitude towards the system will be more positive.
3. Attitude toward using: The user's attitude toward using information technology is affected by perceived usefulness and ease of use.
4. Behavioral intention to use: Behavioral intention determines the use of information systems. It is also affected by an individual's attitude towards technology and the cognitive usefulness of technology.

The development trend of the AEC/FM industry is heading towards the evolution of high-end digital technology. VR technology provides a new design communication experience in response to this evolution. Although many studies have addressed the benefits of BIM and VR in design decision-making, users' acceptance and evaluation of the BIM and VR technology remain to be verified. According to the experimental design and the theory of TAM, this study put forward the following framework of hypotheses, as shown in Figure 6.

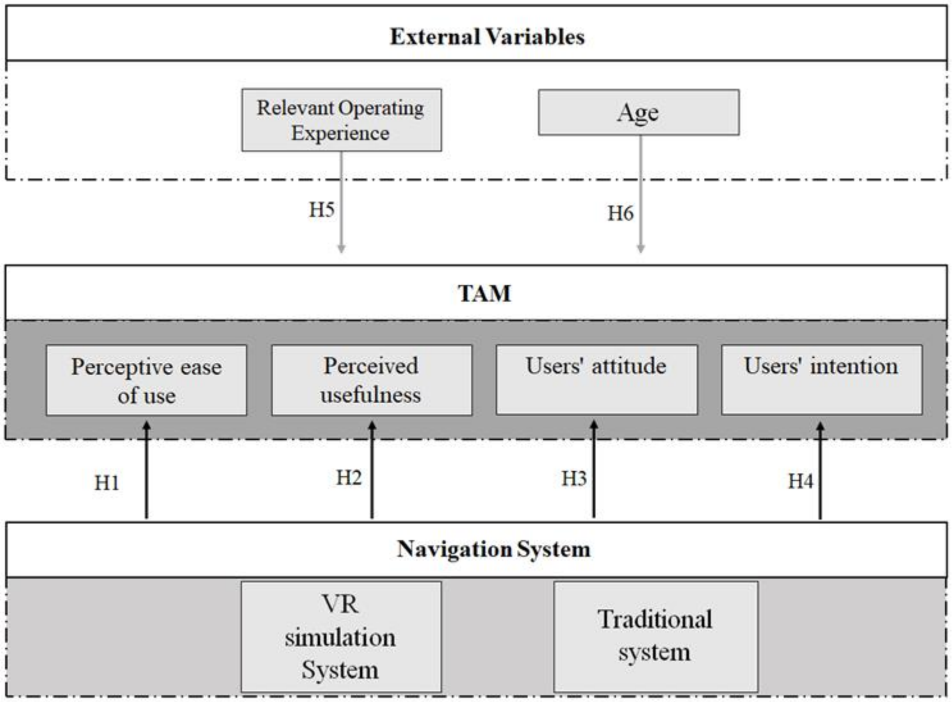


Figure 6 Research hypotheses

H1. The traditional system and the VR simulation system have significant differences in perceived ease of use.
H2. The traditional system and the VR simulation system are significantly different in perceived usefulness.
H3. The traditional system and the VR simulation system have significant differences in user attitudes.
H4. The traditional system and the VR simulation system have significant differences in user's intention.
H5. There is a significant difference in the acceptance of VR simulation system with or without relevant operating experience in the past.
H6. Age variables have significant differences in the acceptance of VR simulation system.

5.0 RESULTS AND DISCUSSIONS

5.1 Statistical Results and Analysis

For the reliability of the questionnaire, the Cronbach's α coefficient, commonly used by sociological research to measure the consistency of question items, was adopted in this study. According to Guilford (1965), the Cronbach's α value < 0.35 means that the question items have low reliability, 0.35 ≦ the Cronbach's α value < 0.7 is acceptable, and the Cronbach's α value ≧ 0.7 indicates high reliability. In this study, the reliability analysis of the four dimensions in the questionnaire was conducted, as shown in Table 1. The result revealed high reliability of the questionnaire.

Table 1 Reliability analysis (Cronbach's α) of the questionnaire

Dimensions	Traditional system	VR
Perceived ease of use	0.784	0.738
Perceived usefulness	0.877	0.850
Users' attitude	0.848	0.725
Users' intention	0.944	0.876

5.2 Hypotheses Verification

Before the hypothesis validation analysis, in our survey, the result of which accepts the hypothesis of normality ($p>0.05$). The paired sample t-test was used to test Hypotheses H1-H4. The test is commonly used for repeated measure design under dependent samples. In the part of perceived ease of use, the result is shown in Table 2. Although the mean value of the VR simulation system is higher than that of the traditional system, there is no significant difference between the pre- and post-test results (p value > 0.05), therefore, H1 is not supported.

Table 2 Hypothesis test of perceived ease of use

Item	Mean	Std. deviation	Mean deviation	*t*	df	*p* -value
Traditional system	3.925	1.049	−0.333	−1.740	29	0.092
VR	4.258					

In terms of perceived usefulness, the mean value of the VR simulation system is significantly higher than that of the traditional system. This result also reveals that there is a significant difference between the pre- and post-test results due to its p value being less than 0.05, as shown in Table 3. Therefore, H2 is supported.

Table 3 Hypothesis test of perceived usefulness

Item	Mean	Std. deviation	Mean deviation	*t*	df	*p* -value
Traditional system	3.187	0.921	−1.193	−7.097	29	.000
VR	4.380					

As for users' attitude, the result of the comparison between the two systems is shown in Table 4. The mean value of the VR simulation system is significantly higher than that of the traditional system, and the p value is less than 0.05. Therefore, H3 is supported. In other words, there is a significant improvement in the users' attitude after using the VR simulation system for project navigation.

Table 4 Hypothesis test of users' attitude

Item	Mean	Std. deviation	Mean deviation	*t*	df	*p*-value
Traditional system	3.227	0.850	−1.227	−7.097	29	0.000
VR	4.452					

Finally, the result regarding the increase of users' intention is shown in Table 5. The mean value of the VR simulation system is also significantly higher than that of the traditional system, and the p value is less than 0.05. Therefore, H4 is supported. It can be inferred that the users' intention has significantly improved after they conducted the building project navigation with the VR simulation system.

Table 5 Hypothesis test of users' intention

Item	Mean	Std. deviation	Mean deviation	t	df	*p*-value
Traditional system	3.450	1.167	−1.067	−5.007	29	0.000
VR	4.517					

From the statistical comparison in Figure 7, we can find that the values of VR system for these four dimensions are significantly higher than the traditional system.

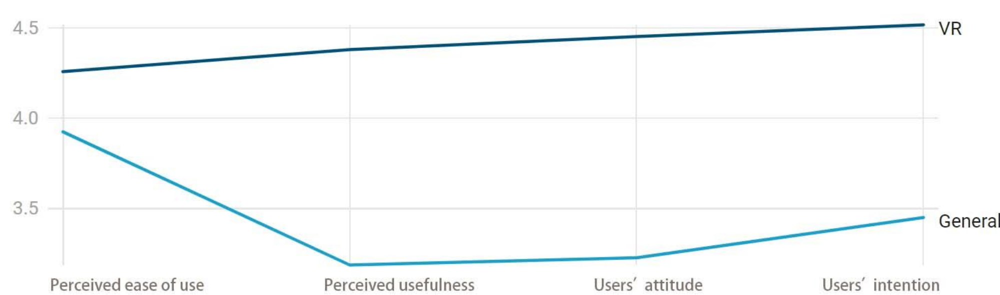


Figure 7 Statistical chart for TAM

In terms of the variable for prior experience in using VR, the result is shown in Table 6. It can be seen that H6 is not supported due to its high p value. This suggests that the prior experience in using VR does not affect the acceptance of using the VR simulation system for building navigation.

Table 6 Acceptance of using the VR simulation system between relevant operating experience in the past

Experience	Mean	Std. deviation	Mean deviation	*t*	df	*p* -value
With experience	4.457	0.199	0.757	0.381	28	0.706
Without experience	4.381					

Finally, for the age variable, the age of the subjects was divided into three groups: 30-40 years old, 41-50 years old, and 51-60 years old. Analysis of variance (ANOVA) was performed for the test, and the results suggest that there is no significant difference in the acceptance of using the VR simulation system in different age groups, as shown in Table 7. Therefore, H7 is not supported.

Table 7 Acceptance of using the VR simulation system among different ages

Age	N	Mean	Std. deviation	F	*p*-value
30-40	8	4.556	0.492	2.20	0.130
41-50	13	4.500	0.336		
51-60	9	4.123	0.610		

6.0 DISCUSSIONS

6.1 Implications for Research Hypotheses

The above statistical tests show that the dimension of "perceived ease of use" still requires more attention and improvement for people using the VR simulation system in the future. This inference is in line with many previous studies suggesting that some users are prone to motion sickness, disorientation, loss of balance, sensory conflicts, and adverse physical or psychological effects during long-term immersive experiences (Juan et al., 2021; Kim et al., 2018; Li et al., 2020; Singh et al., 2021). The hardware should be more lightweight and wireless to improve the comfort of headset wearing. The software design should improve image quality and refresh rate to reduce image delay, while more real-time actions should be made to improve user experience. In other words, in the future a visual scene that is as similar to the actual environment as possible should be developed to avoid sensory conflict caused by the difference between vision and reality.

In terms of usefulness, users' attitudes, and users' intentions, the use of the VR simulation system can have significant values. In other words, users generally believe that the experience of using the VR simulation system in commercial building project navigation is of great help to understanding the project information and spatial details. At the same time, users are also more willing to adopt the VR simulation system as an application for investment and development projects in the future.

Regarding the external variables, the results show that users' acceptance of using the VR simulation system was not affected by their prior experiences of using VR and their age difference. In other words, for users with non-professional backgrounds and of different generations, the introduction of the VR simulation system did not have too many technical barriers. VR could indeed improve the users' understanding of the project and bring significant benefits to developers and potential investors.

6.2 System Evaluation and Feedback

This study further explored the developer team's evaluation of the use of the traditional and VR simulation system into the project briefing. At this stage, thirty experts including project managers, facility managers, and senior executives working on the development team were invited to give feedbacks based on the questionnaire.

The comparison results of the investigation are shown in Table 8 and Figure 8. As seen, the average overall satisfaction of the subjects with the VR simulation system is 4.407 (5 means very satisfied), and the standard deviation is 0.556, while the mean value of the traditional system is 3.148 (standard deviation is 0.589). The difference in satisfaction of using the two different systems clearly verifies that when the developer introduces the VR simulation system into the commercial building project, the project information, workflow, and overall evaluation could all achieve good results.

Table 8 Comparison of the traditional system and VR simulation system

	Traditional		VR	
Questions items	Mean	SD	Mean	SD
1. The spatial experience system is highly realistic for architectural projects	2.767	0.898	4.467	0.681
2. The spatial experience system helps to improve the understanding of building configuration and spatial scale	3.267	0.691	4.100	1.029
3. The spatial experience system helps to enhance the real feeling of spatial scenes	2.600	0.855	4.400	0.621
4. The spatial experience system is helpful for the overall understanding of the commercial building development projects	3.667	0.922	4.467	0.819
5. There is a high willingness to adopt the spatial experience system in the future	3.400	0.855	4.667	0.547
6. The spatial experience system is positive for the project development	3.267	1.143	4.300	0.952
7. The spatial experience system allows decision makers to have confidence in the design results	3.533	0.776	4.633	0.556
8. With the assistance of the spatial experience system, the repeated communication process can be effectively simplified	2.733	0.691	4.300	0.750
9. The spatial experience system is helpful when being applied to the project in all aspects of the building life cycle	2.633	0.765	4.067	1.048
Average	3.148	0.589	4.407	0.500

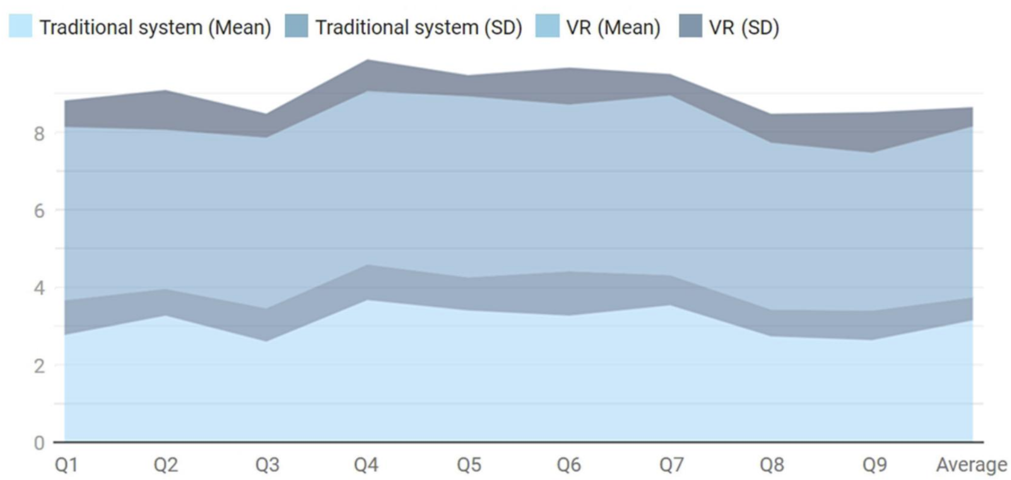


Figure 8 Statistical chart

7.0 CONCLUSIONS

VR, AR, and MR technologies have gradually matured in recent years. The applications of BIM and VR, AR, MR technology have exerted its influence in the AEC/FM industry. Furthermore, users' acceptance and evaluation of VR, AR, MR technology also affect developers' willingness to apply relevant technologies in the future. However, there is relatively little research on the application of the VR, AR, MR technology.

This paper used an actual commercial building project as a case study. Thirty potential investors were invited to compare their experiences in using the VR simulation system and the traditional navigation system. Based on the TAM model, the results show that users believe that the VR system has significant benefits in terms of usefulness, users' attitude, and users' attention. Only the ease of use for the VR system still has room for improvement. Overall, users have given high evaluations to the VR system, and believe that it is helpful to understand the project information, reduce cognitive differences, and improve the spatial experiences. Moreover, the design plan completed by the VR system in this study is the finalized plan. The time and process of design communication, decision making, and investment promotion are significantly shorter than in previous commercial building development projects, and the investment promotion target is achieved in less than one and a half years. The potential investors' inquiry and willingness to invest are also significantly increased.

It is conceivable with the development and innovation of BIM and VR, AR, MR technology that users' acceptance has increased. In the future, industry practitioners can integrate the BIM and VR, AR, MR technology more actively, and introduce it into different stages of the building life cycle, covering pre-development, evaluation, planning, design, construction, operation and management, and investment promotion. Combining the features of VR, AR, MR, which emphasize data visualization and immersive experience, with the parametric design and information communication characteristics of BIM, the VR technology is expected to drive the transformation of the overall industry and bring forth great application values.

Due to the limitations of hardware development, there is still room for improvement in the ease of operation on the hardware and the comfort of the equipment. This also reflects the result of perceived ease of use in this study, in which the users expressed minor doubts about this system. In addition, this study also found that if the project can integrate customized information and present the developers' preferences for spatial planning, materials, and facilities in real-time, the developer's willingness to adopt the Comparisons of the gaze of Areas Of Interest (AOIs) between the traditional and VR simulation system In other words, the VR simulation system developed by this study can present the subjects with a more realistic experience of the virtual space and increase the breadth and depth of the spatial system technology could be greatly increased.

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