Abstract: With technological development and industrial transformation, the architecture, engineering, and construction (AEC) industry, comprising architecture, engineering, and construction, has shifted from a traditional drawing-based design mode to a digital and computer-based mode. In recent years, the application of extended reality (XR) technology, including virtual reality (VR), augmented reality (AR), and mixed reality (MR) technology, emphasizes the immersive and interactive experiences between reality and virtuality, bringing breakthrough developments to architectural projects. This study proposes a new design process mode—the BIM-based XR system—and compares it with the traditional design process mode through an actual stadium design project. Three evaluation perspectives including aesthetics, gaze tracking, and perceived usefulness assessment are used to compare the differences between the two modes. The result showed that the use of the BIM-based XR system could bring users more immersive experience and aesthetic assessment preference, and perceived usefulness in design decision-making, communication, and spatial cognition. The gaze tracking result also revealed that the BIM-based XR system can implement the design process more efficiently. It is expected that XR and BIM technologies can be effectively integrated to enhance the integrity of industrial applications and establish a new design collaboration mode for the AEC industry.

Keywords: sports architecture; virtual reality (VR); augmented reality (AR); mixed reality (MR); extended reality (XR); Building Information Modeling (BIM); gaze tracking

1. Introduction

Immersive technology has been booming with the Fourth Industrial Revolution (Industry 4.0) and industrial changes in recent years [1–3]. Immersive Technology—XR (Extended Reality)—is also known as X-Reality or Cross Reality, which encompasses VR (Virtual Reality), AR (Augmented Reality), and MR (Mixed Reality) [4,5]. Driven by Industry 4.0, the Internet of Things (IoT), and the popularity of portable devices, XR technology has gradually matured [6]. The industry also regards this technology as a method that enhances competitiveness. It reflects its value in many fields, such as consumer industry retail, tourism and entertainment, military technology, commercial display, education, medicine, fashion, architectural design, engineering construction, and real estate sales [6–9]. The AEC industry is highly competitive; various innovative technologies have brought changes, including hand-drawn drawings, physical models, computer graphics, multi-dimensional digital models, and building information models, to the rapid development of XR technology in recent years. XR has the characteristics required for solving distance, space, and time constraints that the previous working mode cannot complete [10–12]. Its application covers the entire building life cycle, enabling real-time interaction between information, virtual, and reality in the construction project and work process. It can also change how
remote collaboration modes make entirely different changes in design, construction, and operation stages and are expected to bring considerable benefits to the AEC industry.

Due to the continuous progress of the world economy and the international development of sports, the global attention to sports events and the number and scale of sports events have been increasing [13–16]—for instance, an experimental stadium project in China. As China moved towards economic reform and opening up in 1978, under the advancing of the times and the change in the overall social environment, many large-scale sports events were held one after another: the 2008 Beijing Olympics, the 2010 Guangzhou Asia Games, the 2011 Shenzhen Universiaede, the 2013 Tianjin East Asia Games, the 2013 Liaoning National Games, the 2014 Nanjing Youth Olympics, the 2015 East Asia Cup, etc. China’s total demand for large-scale sports buildings and venues is also rising. Among countries with relatively high economic development and reasonably advanced technology, the construction of high-standard, multi-functional professional sports venues has become a form of economic and social competition [16,17].

Large-scale sports buildings are often regarded as regional buildings that symbolize national and urban cultural aesthetics [17–19]. However, large-scale sports buildings’ construction and time costs are enormous, and the project’s complexity is also extremely high. It requires the joint investment of project teams across professional fields [20,21]. Especially in the initial planning and design stage, repeated operation procedures are often required in design communication, resulting in a massive waste of labor and time. Moreover, designers and decision-makers often have information asymmetry or cognitive differences, which increases the difficulty of decision-making and is prone to many project disputes. Especially for construction projects with more considerable complexity and scale, it is more difficult to maintain overall project performance and satisfaction [22,23].

In the past, the research on XR in large-scale sports buildings mainly focused on the layout of the space [24–26], building structure, materials, equipment, and physical environment analysis [27–31]. A few studies on design communication, project cooperation, and remote collaboration models apply VR or AR technology in the initial design stage [6,7,10,32–35]. However, XR has proven to be an effective communication aid in the application of construction [9,11,32]. There is more development potential in the future architectural and interior design decision-making processes to effectively integrate and apply the current, maturing XR technology, thereby effectively reducing the gap in situational awareness. Improving the understanding of the scheme, the efficiency of design communication, and providing the customized needs of owners, architects, and related participants to make design decisions are potential future industrial applications.

This study aims to develop a BIM-based XR system for an actual stadium design project. In order to verify the robustness and effectiveness of the system, we employed aesthetic assessments, gaze tracking, and perceived usefulness assessment to compare the feedback differences of the subjects between the traditional design mode and the BIM-based XR system. The project details, specific advantages, and implications of BIM-based XR systems will be discussed in the following sections.

2. The Development of the BIM-Based XR System for Building Design

The design of a large-scale sports building is highly dynamic and complex; it always needs to face different participants [18,36–39]. Traditionally, the job of an architect is to transform the design thinking process into various illustrations (plans, elevations, 3D renderings) according to the needs of the owners [40–44]. However, this design process, as shown in Figure 1, is very time-consuming because project team members may have different interpretations of architectural drawings and spatial information. Once the scheme is modified, it must be approved by all members again before proceeding to the next stage of development. Hence, this process will experience repeated discussions, amendments, confirmations, and evaluations to clarify the problems and requirements, prolonging the overall design process and resulting in the inability to design efficiently. Even after the final decision has been made, the design scheme may be changed due to cost difficulties,
unexpected changing needs of owners, and other external factors; thus, the design scheme has to start all over again. In short, the overall process consumes a considerable amount of time and labor costs for the decision-making process of the design [19,38,45].

Figure 1. Traditional architectural design process.

With the development of information technology, traditional design tools and information exchange will change significantly [46–48]. Through a systematic grasp of user needs, immersive experience (real-time rendering, real-time switching, and presentation of design results by way of virtual and real integration) has demonstrated its efficiency in design discussion, feedback, and project verification [32,48–50]. Some studies have indicated that BIM and immersive technologies can optimize complicated problems of architectural design decision-making, simplify the overall design process, and increase the speed of decision-making and quality [9,11,12,22,35]. For instance, XR technology can provide users with multiple interactions between reality and the virtual in real-time. Users can, therefore, realize the building information and spatial experience through the real-time and interactive functions of VR, AR, and MR, which will be helpful for design decision making. Therefore, this study defines this process based on BIM and immersive technologies, the BIM-based XR system, as a new model for design process, as shown in Figure 2.

Figure 2. BIM-based XR system for design processes.
3. Assessment Methods

Many studies have proposed different assessment methods for the application of immersive technologies [9,51–55]. For example, in order to compare the experience of VR and Stereoscopic Images (SI), Moscoso et al. (2022) provide a Likert-based questionnaire for users to rate subjective experience. Azemati et al. (2020) proposed physical (eye tracking) and psychological (aesthetic scoring questionnaire) measurement methods for the aesthetic evaluation of building facades. Juan et al. (2018) compared VR and traditional design modes, and used a questionnaire based on the technology acceptance model (TAM) to allow subjects to evaluate the system usefulness. Zhang et al. (2019) displayed the virtual environment in a VR headset and used a headset-type eye tracker for 3D eye tracking. Zou and Ergan (2019) displayed a virtual environment on a large screen and used the glasses-type eye-tracking device to measure the user’s viewing behavior. Kim and Lee (2020) used real-world surrounding photos for VR surrounding eye tracking to measure the user experience and visual perception of the built environment, and to infer the users’ attitudes and aesthetic preferences. The above literature reveals the feasibility of using psychological and physiological measures to understand the user’s spatial experience. Considering the necessity of taking into account both psychological and physiological measures, this study uses aesthetic assessment, gaze tracking, and perceived usefulness to evaluate spatial experience under two different design modes.

3.1. Aesthetic Assessment

The aesthetic assessment of architectural design has always been an important part of measuring the design quality of buildings [56]. The aesthetics of buildings, in addition to affecting the overall environment and spatial experience, will also have a certain degree of physical and psychological impact on users [55,57]. Especially in the XR environment, subjective perception of the users’ vision can be used to understand the aesthetics of architectural design. Therefore, in order to verify the differences in the aesthetic assessment of different scheme designs under the two design modes proposed in this study, we use the aesthetic assessment scale proposed by Azemati et al. (2020) to measure the feelings of “like” and “dislike” (0 to 9 Likert scale), as shown in Table 1, to conduct aesthetic assessment of building appearance and interior space for the subjects.

| Score | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|---|
| Aesthetic level | Unlike | Normal | Like |

3.2. Gaze Tracking

Gaze tracking is the process of measuring eye movements to determine where a person is looking, what they are looking at, and for how long their gaze is at a specific spot in real-time [57–60]. It has been widely used in the research of visual systems, psychology, and cognitive linguistics [61–64]. Compared with the traditional questionnaire biased toward the subjective evaluation of the subjects, gaze tracking can objectively collect the data of eye movements for visual behavior analysis. The eye-tracking device is used to observe eye movement differences under the two design modes, providing data on the “invisible” experience that determines human behavior.

In the eye-tracking experiment, the eye-tracking device (Tobii X2-60) and Tobii Pro Studio eye-tracking software are used to image and process the eye movements. The obtained gaze plots, heat maps, and various gaze tracking data will be imported into SPSS for statistical analysis.

3.3. Usefulness Assessment

Technology acceptance model (TAM) is a behavioral model developed by Davis [65] in 1986 based on the rational theory. Its purpose is to find an effective behavioral model
to explain the behaviors and attitudes of users’ acceptance of new information systems in computer science. The model provides a theoretical basis for understanding the influences of external factors on users’ beliefs, attitudes, and intentions, which further affect their use of technologies. The model is also believed to be widely employed to explain or predict the effects of using information technology. In order to understand the experience and evaluation of the two different design modes of the subjects, we simplify and develop the following questionnaire items according to the TAM framework, and mainly measure the perceived usefulness of the system.

- Q1: Compared to the traditional mode, BIM-based XR system can help improve the understanding of the spatial layout and scale;
- Q2: Compared to the traditional mode, BIM-based XR system can help improve the understanding of the feeling of the spatial scene;
- Q3: Compared to the traditional mode, the real-time switching function of communicating new ideas through design is helpful for design cognition;
- Q4: Compared to the traditional mode, the introduction of the BIM-based XR system in design process can help understand the overall project;
- Q5: Compared to the traditional mode, the BIM-based XR system is good for project design;
- Q6: Compared to the traditional mode, the introduction of the BIM-based XR system allows decision-makers to have confidence in the design performance;
- Q7: Compared to the traditional mode, with the aid of the BIM-based XR system, the iterative process will become simple;
- Q8: On the whole, the BIM-based XR system can improve the speed of design decisions compared to the traditional mode.

4. Pilot Case Study

4.1. Project Briefing

The XR development object of this study is a composite stadium design. The construction site is in Zhongmu County, Zhengzhou City, Henan Province, China. The design scheme of this project is to construct three floors on the ground and one floor underground, with a total floor area of 87,749 square meters. The original appearance and the layout of the stadium design are shown in Figure 3. The BIM-based XR system developed in this study is mainly used in the design of a basketball stadium, with a floor area of 12,900 square meters, including basketball courts, lounges, news projection rooms, referee rooms, athletes’ lounges, VIP seats, auditorium, equipment rooms, stairwells, corridors, and other spaces, as shown in Figure 4.

Figure 3. The main BIM model of the composite stadium project.
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Figure 3. The main BIM model of the composite stadium project.

Figure 4. The main BIM model of the basketball stadium.

The research team exports the BIM model of the preliminary scheme built by Autodesk Revit for this project to fbx format, and uses Sketchup and Rhino software to build interior spaces and complex curved building structure. After that, the research team integrates the built 3D model into Revit central model and updates various BIM data. Before importing data into the XR system for presentation, the model materials, lighting, environment, vision, and scene parameters are adjusted in detail to ensure that the subsequent simulated environment is realistic and consistent with the real environment.

Augin plugin is used for the AR part, and Revit Enscape plugin is used for VR & MR parts, and its BIM track function is used to mark the content of problems. In the BIM-Based XR system, when the BIM model is modified, the VR/MR part will render the modification results in real time on the rendering screen conducted by Enscape. AR rendering is through the AR application Augin, which can achieve real-time visualization of BIM model modification. In other words, XR can visualize the BIM model in real time and update the background information and data of the BIM model when design revisions are required. The workflow of the overall BIM-based XR system is shown in Figure 5.

4.2. VR & MR System Development

The VR system is developed by Samsung’s Windows mixed reality headset HMD OLiDARodyssey+, and a wireless six-axis (Degrees of Freedom, DOF) MR somatosensory controller was used. The computer specification is Alienware M15R2; the processor CPU specification is the I7-9750H model. The graphics card GPU model is NVIDIA’s RTX2080 Max-Q 8G version. The computer memory RAM 16G, for computer VR real-time rendering screen transmission and screen calculation and presentation. BIM models are demonstrated using Revit, Sketchup, and Rhino. Enscape is used for real-time rendering of VR scenes, allowing users to take a guided tour of the overall construction project, and experience the broad spatial scale, pattern, texture, and other interactive, immersive experiences. The MR system is presented through Samsung Odyssey+’s MR flashlight function to quickly compare with the actual scene in the virtual space (as shown in Figure 6). The scene includes the project’s indoor, outdoor, and surrounding local environments.
The AR system is presented through the Apple iPad Pro 12.9. The built-in LiDAR optical radar scanner is used to scan the environment, and the scan results provide the AR model for precise positioning. After the two objects are superimposed, they can be displayed on the iPad screen. Architecture and interior design 3D models are built using Revit, Sketchup, and Rhino. The AR software, Augin, is used for actual operations for users to perform the project and experience the overall building configuration. Through the use of AR technology, as shown in Figure 7, building virtual models, drawings, perspectives, and other information can be combined for building navigation so that users can better understand the details of the design scheme.
4.4. Research Process

First, the architect of this project presented a preliminary design scheme and invited the project stakeholders to communicate the scheme. Similar to the result of traditional design mode, this process is very inefficient. After several months, the project team gradually converged to six discrepancies, and at this time, the research team was also invited to join the project team. These discrepancies included:

- Ceiling design and construction: for example, did the design require the use of skylights? Was the ceiling closed? Which structure system was used for the ceiling?
- Hardware equipment: consider the configuration and the location of scoreboards, timers, broadcast stations, and recording studios.
- Lighting design: consider the adoption of anti-glare lamps, indirect lighting systems, or general chandeliers.
- Floor material evaluation: consider the reflection control of the floor and then select the floor material and processing modes.
- Floor color design: consider the experience of users, spectators, and athletes and provide appropriate floor color planning.
- Wall design: consider the visual impact of wall material, color, and form, including detailed sound insulation and sound absorption design.

The architect developed a detailed scheme (Scheme A, as shown in Figure 8) to address these design discrepancies. Meanwhile, the research team was commissioned to complete another design scheme (Scheme B, as shown in Figure 9) based on the BIM-based XR system that can demonstrate the design in real-time rendering, real-time switching, and virtual and real integration. During the development of these two schemes, designers can make multiple design revisions to experience the effectiveness of design communication.
5. Results and Discussions

5.1. Comparison of Two Schemes in Aesthetic Assessment

The research team invited 30 project team members to participate in the questionnaire survey. Of the 30 subjects, eight were experts (architects, contractors, engineering consultants, and electromechanical technicians), eight were government representatives, eight were stadium staff, and six were athletes. None of these subjects had previous experience with VR operation. They were all required to use HMD for VR and MR, and tablet for AR experience, respectively.

The result, as shown in Table 2, showed that the mean value of aesthetic assessment score of Scheme A was 3.87 (SD = 1.68) while Scheme B was 6.53 (SD = 1.50). The t-test, after conducting the normality test to confirm the normal distribution of data, also indicated that there was a significant difference in the aesthetic preference of these two schemes ($p < 0.001$). In other words, the Scheme B, developed based on the BIM-based XR system, can bring users a more immersive experience and aesthetic assessment preference.

Table 2. Aesthetic assessment results.

| Item    | Mean | Std. Deviation | Mean Deviation | t    | df | $p$ Value |
|---------|------|----------------|----------------|------|----|-----------|
| Scheme A | 3.87 | 1.605          | -2.667         | -9.103 | 29 | <0.001    |
| Scheme B | 6.53 |                |                |      |    |           |

These results are supported by Carrasco and Chen (2021), who addressed that the interaction with the real and virtual worlds through XR technology can not only improve the understanding of architecture and interior design, but also convey the design concepts and suggestions of works in the process of information transmission. The integration of related to XR technologies can also enhance the user’s aesthetic experience of the space [66]. In other words, considering the “appropriateness” of aesthetic assessment, the BIM-based XR system is obviously superior to the traditional design mode.
5.2. Gaze Tracking Comparison for Traditional and BIM-Based XR System Design Process

The research team further invited the same 30 subjects to conduct the gaze tracking comparison for the traditional and BIM-based XR system design process, as shown in Figure 10. The test environment is an indoor room with no outdoor light source interference and noise below 40 dB. During the experiment, there is only the subject in the room, and the subject is 60 cm away from the screen. The materials tested are all 4K quality pictures, and the subjects can freely view the pictures during the 15 s of the experiment.

Figure 10. AOs for the traditional system, (a) Scheme A, and BIM-based XR system, (b) Scheme B.

Scheme A is a scheme employed in the traditional design process. The gaze plot is more divergent, which means that users are less able to focus on the main use space and design discrepancies in a stadium design. After the introduction of the BIM-based XR system, users can focus more on the main use space and design discrepancies. In other words, the project team found that the BIM-based XR system can implement the design process mode efficiently.

Figure 11 presents the gaze plot, path, and heat map of the two schemes. Table 3 further records the number of gazes, time (in seconds) of gazes, and trajectories for different spatial areas of interest (AOI) in Figure 11.

Figure 11. Gaze plot, path, and heat map of the traditional system, (a) Scheme A, and BIM-based XR system, (b) Scheme B.

Table 3. Gaze tracking results.

| Design Discrepancies | AOI of Scheme A | AOI of Scheme B |
|----------------------|----------------|----------------|
|                      | Frequency     | Percentage | Seconds | Percentage | Frequency | Percentage | Seconds | Percentage |
| Ceiling              | 8             | 20%        | 3.334    | 22%        | 8         | 20%        | 2.995    | 20%        |
| Hardware             | 1             | 3%         | 0.401    | 3%         | 2         | 5%         | 0.618    | 4%         |
| Lighting             | 0             | 0%         | 0.000    | 0%         | 6         | 15%        | 2.573    | 17%        |
| Floor                | 6             | 15%        | 2.308    | 15%        | 10        | 25%        | 4.105    | 27%        |
| Wall                 | 5             | 13%        | 2.480    | 17%        | 11        | 28%        | 4.032    | 27%        |
| Others               | 20            | 50%        | 6.476    | 43%        | 3         | 8%         | 0.677    | 5%         |
| Total                | 40            | 100%       | 15       | 100%       | 40        | 100%       | 15       | 100%       |
As shown in Table 3, in the same time period (15 s), the users’ gazes in the traditional system were poor (43% belonged to “Other” areas and 0% was in “Lighting” areas), while the BIM-based XR system clearly provided the users with better gaze performance, which means that they can focus evenly on design details in limited AOI areas. There have been many previous studies on gaze tracking and heat maps, which have been used to explore the aesthetic evaluation, psychological feelings, and decision considerations of architectural design [67–69]. The results of this experiment can also verify the effectiveness of the BIM-based XR system.

5.3. Comparison of Two Schemes in Perceived Usefulness

In addition to the aesthetic evaluation and gaze tracking verification, this study also provided a set of questionnaires in the final stage of the study to verify the perceived usefulness of the BIM-based XR system, compared to the traditional mode. The experiments were performed in a quiet and undisturbed laboratory. The experiments were divided into pre-test (spatial experience based on the traditional design mode) and post-test (spatial experience based on the BIM-based XR system). In order to avoid knowledge overlap and experimental fatigue, as well as decrease the influence of the pre-test, the subjects were invited again to be tested by the BIM-based XR system after 14 days. Both of the experiments were conducted for 30 min, and when the experiments were completed, the subjects were asked to conduct the perceived usefulness assessment.

The results, as shown in Table 4, showed that the overall mean value of the subjects was 4.50 (5 means “strongly agree”), and the standard deviation was 0.16, which revealed that the new model of design process proposed in this study could achieve good results in design decision-making, communication, and spatial cognition.

| Question No. | Item          | Mean | Std. Deviation | Mean Deviation | t   | df | p Value |
|--------------|---------------|------|----------------|----------------|-----|----|---------|
| Q1           | Traditional   | 3.43 | 1.062          | −0.900         | −4.64 | 29 | <0.001 |
| Q1           | BIM-based XR  | 4.33 |                |                |     |    |         |
| Q2           | Traditional   | 2.73 | 0.995          | −1.900         | −10.46 | 29 | <0.001 |
| Q2           | BIM-based XR  | 4.63 |                |                |     |    |         |
| Q3           | Traditional   | 3.63 | 0.986          | −0.833         | −4.63 | 29 | <0.001 |
| Q3           | BIM-based XR  | 4.47 |                |                |     |    |         |
| Q4           | Traditional   | 2.70 | 1.029          | −1.900         | −10.11 | 29 | <0.001 |
| Q4           | BIM-based XR  | 4.60 |                |                |     |    |         |
| Q5           | Traditional   | 3.50 | 1.236          | −0.700         | −3.10 | 29 | 0.004  |
| Q5           | BIM-based XR  | 4.20 |                |                |     |    |         |
| Q6           | Traditional   | 3.50 | 1.203          | −1.000         | −4.55 | 29 | <0.001 |
| Q6           | BIM-based XR  | 4.50 |                |                |     |    |         |
| Q7           | Traditional   | 3.57 | 1.287          | −1.000         | −4.26 | 29 | <0.001 |
| Q7           | BIM-based XR  | 4.57 |                |                |     |    |         |
| Q8           | Traditional   | 2.90 | 1.305          | −1.567         | −6.58 | 29 | <0.001 |
| Q8           | BIM-based XR  | 4.47 |                |                |     |    |         |

The results are highly consistent with many previous studies showing that BIM combined with XR is indeed highly feasible as a design aid and decision-making tool, and it can also improve the overall workflow and stimulate the creativity of users [9–11,32,34]. However, due to limitations in hardware and software, the head-mounted device still has some obstacles to be overcome for users. For example, long-term wear comfort, battery
life, presentation of large-capacity and highly complex 3D models, accurate environmental positioning and tracking, multi-user simultaneous remote collaboration, and improvement of human–computer interaction modes. Reviewing and refining the deficiencies of these technologies will bring better experience and applications to the industry.

6. Conclusions and Suggestions

The development of XR technology has reshaped the situation where virtual reality and reality are intertwined. It also expands human perception and drives the pace of the digital transformation of the product and service models. In terms of industrial applications, XR has become a mature integrated application of emerging digital technologies that can provide a more profound sense of immersion, interaction, and imagination and bring a full range of innovations and opportunities for today’s COVID-19 epidemic prevention era.

Traditional design communication cannot ensure the accuracy of information exchange between different project members, resulting in many inefficient communication situations and affecting project executions. The results of this study showed that the BIM-based XR system could not only improve users’ aesthetic assessment, immersive experience, and design efficiency of design schemes, but users also had high satisfaction with the system’s usefulness. More importantly, it can reduce cognitive differences among project stakeholders and improve the perception of space and communication efficiency.

In terms of research limitations, although this study verifies the application and benefits of the BIM-based XR system, it is still difficult to comprehensively cover many design details, construction methods, building forms, equipment pipelines, and material selection for complex and large-scale projects. Therefore, in the future, it is suggested that digital design and immersive technology be used in different design stages, and the concept of BIM be integrated for complete and comprehensive decision-making assistance. Moreover, this study used eye tracker data to assist subjective evaluation, which is still a preliminary application. In the future, it is suggested that the BIM-based XR system be combined with various physiological measurement tools (such as eye trackers, heart rhythm variability detection instruments, and brain wave instruments) in the design stage to analyze the physiological value changes of users in different spatial experiences and further grasp more user needs.

Author Contributions: Conceptualization, S.L.; methodology, H.-Y.C. and Y.-K.J.; performed the evaluations, H.-Y.C. and Y.-K.J.; analyzed the data, H.-Y.C. and Y.-K.J.; writing—original draft preparation, H.-Y.C. and Y.-K.J.; writing—review and editing, H.-Y.C. and Y.-K.J.; visualization, H.-Y.C. and S.L.; supervision, Y.-K.J. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the funding supported by the Taiwan Building Technology Center from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan (grant number: 111P011, 2022).

Data Availability Statement: The data that support the findings of this study are available from the first author, H.Y.C., upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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