VRDR

An Attempt to Evaluate BIM-based Design Studio Outcome Through Virtual Reality

FAUZAN ALFI AGIRACHMAN[1] and MICHIHIKO SHINOZAKI[2]
[1,2]*Department of Architecture, Shibaura Institute of Technology, JAPAN*
[1,2]*{na19503|sinozaki}@shibaura-it.ac.jp*

Abstract. During the COVID-19 pandemic situation, educational institutions were forced to conduct all academic activities in distance learning formats, including the architecture program. This act barred interaction between students and supervisors only through their computer's screen. Therefore, in this study, we explored an opportunity to utilize virtual reality (VR) technology to help students understand and evaluate design outcomes from an architectural design studio course in a virtual environment setting. The design evaluation process is focused on building affordance and user accessibility aspect based on the design objectives that students must achieve. As a result, we developed a game-engine based VR system called VRDR for evaluating design studio outcomes modeled as Building Information Modeling (BIM) models.

Keywords. Virtual reality; building information modeling; building affordance; user accessibility; architectural education.

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic situation has forced architectural education institutions worldwide to arrange their academic activities differently. Institutions organize online classes, workshops, and design studios to avoid any viral community transmission within students and supervisors. Unfortunately, both students and supervisors have difficulties involved in an architectural design studio, a hands-on practice, and assessment by nature (Allam et al., 2020). Students cannot present their design works appropriately in front of their screen, and it is hard for supervisors to engage with students' works without any direct hands-on session. It needs a technology that can bridge them gearing verbal presentation, discussion, and assessment in a learning process (Lymer et al., 2009). By looking at the phenomenon, we are interested in investigating virtual reality (VR) technology utilization to help students and supervisors in the design learning process - especially in the design evaluation process, as part of the decision-making process.

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 223-232.

In past years, researchers found that students get benefits that help their learning process understand the architectural space and design process using VR technology in architecture education. Dvorak et al. (2005) showed that VR helps increase students' speed and insight in learning architecture. They also found that VR is suitable for students to understand modeling and design faster because they focus on more prominent issues. Horne and Thompson (2008) found that VR technology can extend students' learning processes and improve their motivation and awareness. VR provides the sense of "being there" with immersive interaction between students and their design works. It is considered vital because behavior, cognitive outcomes, and users' subjective experiences must be taken into account by the architectural designer when evaluating a building design using VR (Kuliga et al., 2015).

Researchers also studied that the design evaluation process has become one of the important use cases of VR technology in the architectural, engineering, and construction sectors. VR provides a more efficient design review process and helps stakeholders identifying issues easier (Davila Delgado et al., 2020). VR is also able to assist architectural designers for space assessment ranging from spatial relationship, occupation comfort, visual and audio comfort (Berg and Vance, 2017; D'Cruz et al., 2014; Echevarria Sanchez et al., 2017; Liu and Kang, 2018; Sun et al., 2020). VR also can help non-designer to examine architectural design with ease (Serpa and Eloy, 2020). Even after the design development phase, VR can support stakeholders during the construction phase by providing improved communication between professionals, visualizing design review scenarios in construction, and analyzing building constructability (Bassanino et al., 2010; Boton, 2018; Dinis et al., 2020). Besides, VR usage for design evaluation in the operational phase is also explored. (Akanmu et al., 2020) Although there has been much research on VR for the design evaluation process, VR utilization for architectural design studio evaluation has not been explored much. Therefore, in this study, we explore VR utilization to help students evaluate their design outcomes in an architectural design studio course by developing a game engine-based VR system.

2. Research Method

This study uses a simulation research method (Groat and Wang, 2013) by transforming the design studio outcomes into a real-world setting as a virtual environment and drive individual perceptions of anyone who interacts inside it. We worked with students' design studio outcomes retrieved from the faculty archive. Since selected outcomes were authored as Building Information Modelling (BIM) models, we took advantage of them to enhance user experience inside the VE. This study aims to offer a VR system for evaluating design studio outcomes based on the design objectives assigned in terms of references (TOR) document of the studio course, focused on two components: building affordance and user accessibility.

3. Defining Design Evaluation Components

Before performing the design evaluation process, design evaluation parameters must be defined from both components: building affordances and user accessibility. First, the building affordance concept was derived from The Theory of Affordances, coined by Gibson in 1979 (Gibson, 2014). He described "affordance" as "what it offers the animal, what it provides or furnished, either for good or ill.". For example, in a house, a floor affords a person to walk from one room to another room, and a door affords a person to enter and exit a room. It means that the floor has an affordance of moving between rooms, and the door has an affordance of accessing a room in the house. Simultaneously, a thing can have more than one affordance, whether it is good or bad for a user. For example, a ramp affords a person to move from one place to another place with a different level of height, and at the same time, the ramp also affords a person to slip and fall to the ground. It shows that a ramp has one positive affordance and one negative affordance. Those affordances might be changed because Gibson mentioned that different places of habitat or a built environment might have different affordances.

From an architectural design point of view, Koutamanis (2006) pointed out that the concept of affordances has the potential ability to understand and utilize the different aspects of users. Architects and architectural designers can use affordance as a design approach to go beyond user-profile generalization and understand how people, as their works' end-users, will use the space. Different user has different affordances of the place that they belong. The architect maps the affordances within their design and eventually use them as feedback to improve the final design before it moves to the construction process.

In the design evaluation process, the concept of affordances clearly can be adopted for evaluating design works. An architect can learn and use affordances to determine appropriate goals that he wants to achieve as the final product, as Maier et al. (2009) described. Affordances can be used to understanding failures and unintentional design consequences, including unexpected human behavior. In the end, a design that affords users to do intended behavior and activities by an architect is considered a successful design. Especially when an architect can evaluate and confirm different intended affordances for different users existed in their design. It can be recognized from a large building or room-scale to a small interior scale, such as a ramp or door handle.

For this study, the design outcome's affordances were identified from design objectives mentioned in the TOR document using predetermination strategy. This strategy starts by determining artifact-user affordances (AUA) and artifact-artifact affordances (AAA). The desired studio outcome should have and not have from each design objective as an affordance structure. In short, AUA defines a relationship between a built environment and a human user situated in it. While in AAA, an affordance defines a relationship between an element and other elements in their respective built environment where behavior can exist in it. All identified affordances were mapped in the form of Affordance Structure Matrix (ASM) developed by Maier et al. (2008), as seen in Figure 1. The Matrix is used as an evaluation tool and combined with VR.

Affordance Structure Matrix			Room										Building Component									
			Retail	Atrium	Café	Gym	Karaoke	Minimarket	Toilet (Ladies)	Toilet (Gents)	Toilet (Disabled)	Circulation Area	Slab	Str. Column	Str. Beam	Ramp	Solid Wall	Glass Wall	Railing	Stairs	Ceiling	Facade
+AUA	G1	Safety in activities																				
	G2	Comfort in activites																				
	G3	Suitability of activities with the function of space																				
−AUA	H1	Getting in an accident																				
	H2	Getting lost in the building																				
+AAA	J1	Ability to support the load																				
	J2	Natural ventilation																				
−AAA	K1	Chances of getting hot easily																				
	K2	Excessive glare																				

Figure 1. Affordance Structure Matrix.

The second evaluation component that must be identified is user accessibility. For this study, we are considering a wheelchair user as a study case. Arlati et al. (2019) studied that wheelchair users' movement simulation using VR and HMD devices should be contextualized with the simulated living environment. This step will increase realism that contributes to the VR system's effectiveness for simulating the accessibility of wheelchair users in an environment. As a measurement standard, we use the standard maneuver diameter of a wheelchair user based on the Law of Ease of Building Standard released by the Ministry of Public Works and Housing of Indonesia (2017), as seen in Figure 2. The maneuver diameter of a wheelchair user is 152,5 centimeters in minimum.

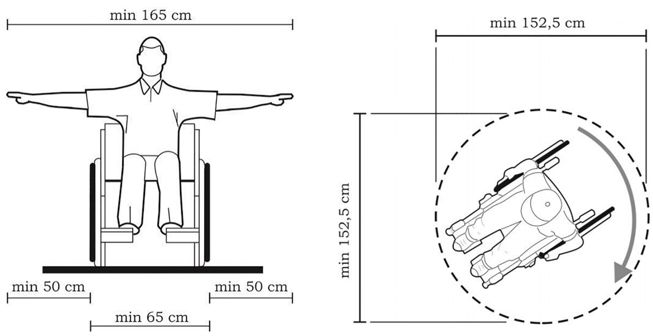

Figure 2. Maneuver diameter for a wheelchair user (Ministry of Public Works and Housing of Indonesia, 2017).

4. VRDR: An Attempt for Design Evaluation in Virtual Reality

After design evaluation parameters were specified, we developed a game engine-based VR system called Virtual Reality Design Reviewer (VRDR). The system was developed using Unity game engine technology and optimized for standalone VR head-mounted display such as Oculus Quest. This decision was made to have VRDR run without a need for high-end personal computer (PC) specification. VRDR lets the user himself explore design studio outcomes in a BIM model inside a VE.

VRDR consists of three system layers: BIM models as 3D geometric and building instance parameter data sources; design evaluation as a decision-making process, user interface (UI), and user experience (UX) layers, as shown in Figure 3. First, as mentioned above, all design studio outcomes used in this study are modeled as a BIM model. Three-dimensional geometries from the BIM model were imported into the .obj file and optimized for VR. We extracted essential parameters from several instances, such as name, area, and volume, to add an informative layer to UI and UX layers. More explanation on how those models and parameters are used in VRDR will be discussed in the next subsection. Second, we put design evaluation as the decision-making process of an architectural design at the center of VRDR. The design evaluation process will be focused on two main design evaluation components: building affordances and user accessibility. The third is the UI/UX layers, consisting of three sublayers: multisensory & spatio-temporal aspect of VR system; architecture design studio nuances in a VE; and positioning students and supervisors as system users.

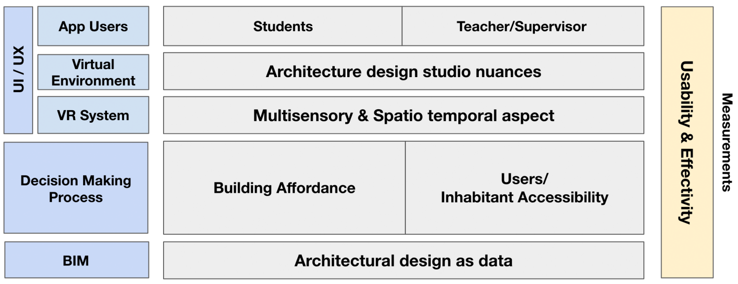

Figure 3. VRDR System Layers Diagram.

4.1. SYSTEM FRAMEWORK

VRDR system framework contained three main parts: Common Data Environment (CDE) of the BIM; VR model; and a standalone VR HMD device connected to the Internet, as shown in Figure 4. CDE worked as the back-end arrangement for VRDR, where the database needed for the system resides. VR model contained all optimized objects with embedded material textures and properties from the BIM models, a representative state transfer (RESTful) client as the connector to the database inside the CDE, and a world space-based UI UX to enable user working with the BIM model inside the VE. Then, the VR model is deployed to the standalone HMD device. It must be connected to the Internet for connecting with databases in the CDE.

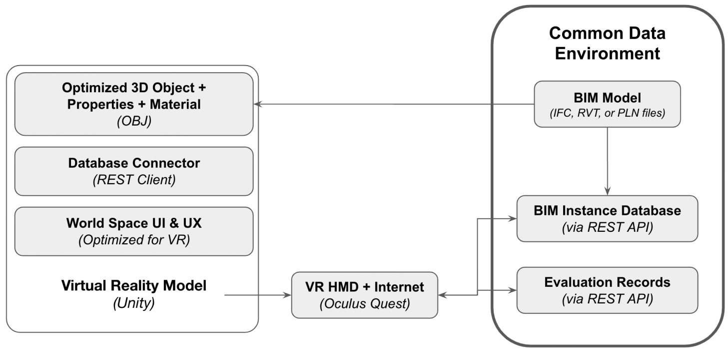

Figure 4. VRDR System Framework.

CDE or BIM repository collects and manages all BIM-based information and objects of individual projects (Sacks et al., 2018). We used a custom arrangement of cloud services and storage adapted from the previous preliminary study (Agirachman and Shinozaki, 2020). There were BIM models of design studio outcomes, instance database, and design evaluation records database in the CDE. The database was filled with the parameters and values extracted from the BIM models and connected to VRDR via RESTful Application Programming Interfaces (RESTful API). It allowed easy data request and storing process by VRDR to the databases.

After preparing the CDE, we developed the VR model in VRDR by exporting the three-dimensional objects from the same BIM models, including their materials. The objects were optimized by reducing their Level of Detail (LoD) and numbers of triangulations. This step is crucial to maintain the VR real-time rendering performance done by the HMD device. It is also helpful to reduce motion sickness that happened to a user when using the VRDR system. Unique object identifiers such as object identification number were also extracted from the BIM models to VRDR to link the object with the instance database set up in the CDE. So, each object could fetch related information via the RESTful API provided in the CDE.

Then, we developed UI inside the VR model to help the user interact with the models, both general and specific tools for the design evaluation process. General tools, such as input keyboard, show and hide buttons, environment adaptor panel; and project information panel, were placed in front of the user avatar for easier reachability. Specific tools such as object tags were placed near their respective object instance; questionnaire panel and scene switcher were placed in the same location along with the general tools. The questionnaire panel was designed to let the user load questions and record feedback to the CDE database. So, we can retrieve the evaluation response faster regardless of the VRDR user location.

For user accessibility evaluation, the system was equipped with a wheelchair simulator with a detector ring around it. The simulator will help the user evaluate the building design if it is suitable for a user with a wheelchair to easily maneuver.

The ring would react if it collided with nearby specified building components such as a wall or door. Ring interaction will be ignored if it has only collided for two seconds or less to avoid any false positive recorded.

4.2. SYSTEM WORKFLOW

In the beginning, the user will be asked to wear the VR HMD device and launch the VRDR application in it. Once the application is started, the user will see the general tools in front of him with the environment adaptor panel and scene selectors. Users will choose a scene of design outcome to evaluate by using a VR controller on their hands.

By default, the user will be in wheelchair mode, where the user can move slower, and the eye position is lower than the normal standing position. The user will be asked to explore all the building sections as a VR model to check whether its design complies with the wheelchair maneuver standard. The detector ring is enabled with green color by default. When it collides with a wall, the ring color turns yellow, and a warning panel appears in the general tools area, as seen in Figure 5. The ring also records the colliding duration and coordinates, which later can be regenerated as a heatmap. That is the workflow for user accessibility evaluation.

The user can then disable the wheelchair mode to move freely in the virtual environment to start building affordance evaluation. For this study, we put a room tag panel linked to the spatial properties of each room. Users can check the information of each room and type their feedbacks using the input keyboard available. After examining all rooms in the building, the user can answer all questions related to building affordance. All user inputs will be sent and stored in the database.

Figure 5. Wheelchair simulator ring turns green when the surrounding space affords the user to maneuver well (left) and turns yellow when the space doesn't (right).

5. Discussion

This section will discuss how the VRDR system works; the original features that make it distinctive; the advantages and disadvantages of the current systems; and opportunities that should be addressed in future studies. VRDR system combines the immersive of VR technology and the power of embedded information inside 3D geometries of a BIM model. It enables the student to get a sense of how his design would be built virtually on a scale of 1:1. By adding information layers from the extracted BIM database, the student can gain more spatial awareness of which area he is currently exploring. It is like playing a first-person video game, but the environment he explores is the building and site design he created by himself. In VRDR, students can evaluate if their designs afford the building users to perform activities mentioned in the TOR document of the design studio and comply with ease of building standard - more specifically for wheelchair users.

VRDR system offers original features that make it distinctive from others. The system has a RESTful client and API built-in, enabling both structured and unstructured data connection. A structured data connection is needed to access structured databases such as the instance database, which contains instance name, width, length, and location. Unstructured data connection availability lets us have a feedback feature where users can type textual feedback, send it to the CDE, and be accessed with other users for review. The system also has a wheelchair mode with a detector ring that helps student evaluate their design compliance with wheelchair maneuver standards. The ring also uses RESTful API to send location coordinate where it gets triggered. We can map the coordinate and check which part of the building has not complied with the standard.

There are advantages and disadvantages of the current VRDR system that we can identify. The VR model linked to the CDE database in the cloud enables the student to update the model information directly inside the virtual environment or outside with a separate dashboard. This advantage opens an opportunity to elaborate it with the design authoring modification process. The student can change specific building components or properties and record all changes to the CDE database. Students can send notes or feedback in text by typing them in the room tag panel and record it as part of their design logbook. Since the current system is in single-player mode, only one student or user can interact with the VR model at a time. Multi-player mode within the VRDR system is an opportunity in a future study. It would be helpful for students and even supervisors to evaluate design outcomes together in real-time.

In terms of the design evaluation process, user accessibility evaluation used in VRDR is still limited for wheelchair users and focuses on wheelchair maneuver radius compatibility. Other detailed factors such as small gaps between floors that can make a user with a wheelchair stuck in it or friction factor between wheels and floor material should be considered to add in the future to have a more realistic simulation. Building affordance evaluation in the study is still considered a self-evaluation where the user evaluates the design by filling the Affordance Structure Matrix. Unlike user accessibility evaluation, where users can use a technical standard to evaluate design compliances quantitatively, building affordance evaluation depends on the cognition skill of each user who experiences it. The evaluation still needs confirmation from third-party, i.e., other students or supervisors, to check if the design has the affordances shown in the Matrix.

6. Conclusion

VRDR system enables students to utilize VR technology to evaluate their design outcomes, mainly in user accessibility, building affordances, and design confirmation aspects. Student can use VRDR to check if his design complies with ease of building standard for wheelchair users and automatically record the spots in the rooms which do not comply with the standard for further analysis. Using Affordance Structure Matrix, the student can evaluate if building affordances based on the design studio objectives have existed in his design outcome. As the outcomes were authored as BIM models, students can get additional information about their design, such as room properties. The instance database provided information in the CDE and linked to each 3D geometry inside the virtual environment.

The next stage of this study is the analysis process of results recorded by the system. The authors will take the step to find out any differences between non-VR and VR system-equipped design evaluation processes, the advantages, and disadvantages of both methods for the student to get more insights into how the VR system can improve their design works. After that, further development of the system will be discussed based on the analysis result.

References

Agirachman, F.A. and Shinozaki, M.: 2020, BINDING DIGITAL AND PHYSICAL ENTITY: ASSEMBLING INTERACTION MODEL USING VIRTUAL REALITY AND BUILDING INFORMATION MODELING, *SEATUC journal of science and engineering*, **1**, 26-31.

Akanmu, A., Olayiwola, J. and Olatunji, O.: 2020, Automated checking of building component accessibility for maintenance, *Automation in Construction*, **114**, 103196.

Allam, Z., Siew, G. and Fokoua, F.: 2020, "How COVID-19 Will Shape Architectural Education" . Available from <https://www.archdaily.com/939423/how-covid-19-will-shape-architectural-education> (accessed 2nd November 2020).

Arlati, S., Colombo, V., Ferrigno, G., Sacchetti, R. and Sacco, M.: 2019, Virtual reality-based wheelchair simulators: A scoping review, *Assistive Technology*, **32**(6), 293-305.

Bassanino, M., Wu, K.C., Yao, J., Khosrowshahi, F., Fernando, T. and Skjærbæk, J.: 2010, The impact of immersive virtual reality on visualisation for a design review in construction, *Proceedings of the International Conference on Information Visualisation*, 585-589.

Berg, L. and Vance, J.: 2017, An Industry Case Study: Investigating Early Design Decision Making in Virtual Reality, *Journal of Computing and Information Science in Engineering*, **17**, 1-7.

Boton, C.: 2018, Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation, *Automation in Construction*, **96**, 1-15.

D'Cruz, M., Patel, H., Lewis, L., Cobb, S., Bues, M., Stefani, O., Grobler, T., Helin, K., Viitaniemi, J., Aromaa, S., Frohlich, B., Beck, S., Kunert, A., Kulik, A., Karaseitanidis, I., Psonis, P., Frangakis, N., Slater, M., Bergstrom, I., Kilteni, K., Kokkinara, E., Mohler, B., Leyrer, M., Soyka, F., Gaia, E., Tedone, D., Olbert, M. and Cappitelli, M.: 2014, Demonstration: VR-HYPERSPACE - The innovative use of virtual reality to increase comfort by changing the perception of self and space, *Proceedings - IEEE Virtual Reality*,

167-168.
Davila Delgado, J., Oyedele, L., Demian, P. and Beach, T.: 2020, A research agenda for augmented and virtual reality in architecture, engineering and construction, *Advanced Engineering Informatics*, **45**, 101122.
Dinis, F., Sanhudo, L., Martins, J. and Ramos, N.: 2020, Improving project communication in the architecture, engineering and construction industry: Coupling virtual reality and laser scanning, *Journal of Building Engineering*, **30**, 101287.
Dvorak, J., Hamata, V., Skacilik, J. and Benes, B.: 2005, Boosting up Architectural Design Education with Virtual Reality, *Central European Multimedia and Virtual Reality Conference*.
Gibson, J.: 2014, *The Ecological Approach to Visual Perception, Classic Edition.*, Taylor & Francis, New York.
Groat, L. and Wang, D.: 2013, *Architectural Research Methods*, John Wiley & Sons, Inc, Hoboken, New Jersey.
Horne, M. and Thompson, E.: 2008, The Role of Virtual Reality in Built Environment Education, *Journal for Education in the Built Environment*, **3**, 5-24.
Koutamanis, A.: 2008, BUILDINGS AND AFFORDANCES, *Design Computing and Cognition '06*, 345-364.
Kuliga, S., Thrash, T., Dalton, R. and Hölscher, C.: 2015, Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model, *Computers, Environment and Urban Systems*, **54**(November 2015), 363-375.
Liu, F. and Kang, J.: 2018, Relationship between street scale and subjective assessment of audio-visual environment comfort based on 3D virtual reality and dual-channel acoustic tests, *Building and Environment*, **129**, 35-45.
Lymer, G., Ivarsson, J. and Lindwall, O.: 2009, Contrasting the use of tools for presentation and critique: Some cases from architectural education, *International Journal of Computer-Supported Collaborative Learning*, **4**, 423-444.
Maier, J., Ezhilan, T. and Fadel, G.: 2007, The affordance structure matrix - A concept exploration and attention directing tool for affordance based design, *2007 Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007*, 277-287.
Maier, J., Fadel, G. and Battisto, D.: 2009, An affordance-based approach to architectural theory, design, and practice, *Design Studies*, **30**, 393-414.
Sacks, R., Eastman, C., Lee, G. and Teicholz, P.: 2018, *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, Third Edition*, John Wiley & Sons, Inc, Hoboken, New Jersey.
Echevarria Sanchez, G., Van Renterghem, T., Sun, K., De Coensel, B. and Botteldooren, D.: 2017, Using Virtual Reality for assessing the role of noise in the audio-visual design of an urban public space, *Landscape and Urban Planning*, **167**, 98-107.
Serpa, F. and Eloy, S.: 2020, How non-designers understand the architecture design project : a comparative study using immersive virtual, *Interaction Design and Architecture(s) Journal*, **45**, 287-301.
Sun, L., Tan, W., Ren, Y., Ji, X., Wang, Z. and Li, P.: 2020, Research on Visual Comfort of Underground Commercial Streets Pavement in China on the Basis of Virtual Simulation, *International Journal of Pattern Recognition and Artificial Intelligence*, **34**(3), 2050005-1-2050005-23.