A COLLABORATIVE PLANNING MODEL FOR OFFSITE CONSTRUCTION BASED ON VIRTUAL REALITY AND GAME ENGINES

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ABSTRACT: *Accurate process planning is essential for successfully implementing offsite construction projects. New technologies, such as virtual reality (VR), have been proposed as potential proactive solutions that allow users to experience and train on OSC processes to ensure safety and efficiency in an immersive environment. However, current VR applications in OSC projects (VR-OSC) problems are limited to residential projects and target single phases of the OSC implementation. This study proposes a VR framework to train participants on modular bridge construction processes. The developed model comprises several OSC phases, such as fabrication, transportation, and assembly. Furthermore, the study explores the use of collaborative platforms that can be associated with the VR model to ease the model and the developed scenes. The model is tested on a sample of participants that evaluated the performance of the model and provided areas of improvement. The results showed the capabilities of the model in providing an immersive experience for participants and connecting different phases of the OSC projects. Also, the results show that the experiment length and complex controlling buttons are among the areas of improvement. The developed model is expected to facilitate safe and efficient training for complex OSC projects.*

KEYWORDS: *Offsite Construction, Building Information Modeling, Virtual Reality, Game Engines*

1. INTRODUCTION

As the conventional construction method has been argued to provide less productivity compared to other industries, offsite manufacturing and modularization solutions have been proposed to enhance the efficiency of the construction industry (Alsakka et al., 2023; Hussein et al., 2022). Modular construction, as a part of offsite construction (OSC), is the process of assembling fully finished modules in the factory, transporting them to the job site, and installing them in the correct locations (Assaf et al., 2023). However, the efficient adoption of modular construction requires a high level of information technology and digitalization (Ezzeddine & García de Soto, 2021). Hence, various digital solutions and technologies have been adopted in modular construction methods, including computer vision (Alsakka et al., 2023), blockchain (Wu et al., 2022), Internet of Things (IoT) (Li et al., 2022), and immersive technologies (Zhang et al., 2023).

Virtual reality (VR), as a part of immersive technologies, has been used by many researchers to enhance the implementation of OSC techniques. VR can be defined as a simulation of the real world in which participants can interact with the virtual assets and experience different degrees of immersion in the simulated environment (Abbas et al., 2019; Alrehaili & Al Osman, 2022). These degrees of virtual immersion include non-immersive, semi-immersive, and fully immersive VR models (Zhang & Pan, 2021). The virtual scenes in the simulated environments are usually done using game engines (Olofsson, 2018). Through the use of game engines, the interaction rules and conditions are defined using coding scripts (Kumar et al., 2011). This combination of VR and game engines have been used in several research domains, such as health and therapy treatment (Mevlevioğlu et al., 2022), the food and shopping industry (Gil-López et al., 2023), and the construction industry (Boton, 2018).

As the combination of VR and game engines is a promising approach in many industries, OSC also benefited from it. The VR-OSC research has gained massive attention in recent years. For instance, Zhang and Pan (2021) have proposed a VR model of tower crane location planning for modular construction projects. The model was created using the Unity3D game engine and was supported by a graphical user interface (GUI) to facilitate the selection of crane types, layout plans, and camera views. Similarly, Shringi et al. (2023) aimed to develop a VR model to train operators on crane operations in offsite construction. Their model included a safety index that was calculated based on penalties applied to each of the identified risks in the scene. In safety and ergonomics analysis, Dias Barkokebas et al. (2022) combined a VR model with a motion capture system to evaluate workers' ergonomics in OSC factories. The VR model was developed using Unreal Engine, and the data collected through the motion capture technology was analyzed using rapid entire body assessment (REBA) and rapid upper limb assessment (RULA) methods. Similarly, Joshi et al. (2021) proposed a VR safety training model for precast factories for

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employees. The model was developed using Unity3D and was used to train the employees on the personal proactive equipment (PPE), stressing processes, and safety measures in the factory. Inyang et al. (2012) developed a VR model to assess safety risks in panelized construction factories. Their model evaluated different layouts of the manufacturing facility, and ergonomic risks were evaluated for each of the selected layouts.

For educational purposes, VR has proven to be an effective tool in educating participants and students on OSC processes (Eiris et al., 2020). For instance, Beh et al. (2022) introduced an educational model to train students on inspection activities of the OSC projects. Game engines were used in their model to develop educational game scenes, including fire inspections, leak inspections, and rain system inspections. Similarly, Sampaio and Viana (2014) created a VR model to educate students on the processes included in the prefabricated bridges. Furthermore, VR-OSC research also targeted the use of VR in evaluating design alternatives and factories/site layouts. For instance, Zhang et al. (2006) have developed a VR model to help participants in evaluating design alternatives in prefabricated construction. Their model assessed many criteria, including production time and cost. Zhang et al. (2021) developed a virtual environment to improve the generated value to the customer in offsite construction facilities. Many other applications of VR-OSC research were found in the literature, including collaborative digital platforms in modular construction projects (Ezzeddine & García de Soto, 2021) and the use of VR in circular economy of OSC projects (O'Grady et al., 2021).

Despite the contribution provided by the previous studies, they lacked the following aspects: 1) all of the mentioned studies have considered the use of VR in OSC residential projects. OSC, especially modular construction, can be employed in many project types, such as bridge construction, which is usually referred to as modular bridges (Lechner et al., 2021). Modular bridge construction includes fabricating heavy steel and concrete modules in manufacturing facilities and shipping them to the bridge to be aligned and installed (Xiangmin & Dewei, 2021); 2) most of the presented studies have tackled the OSC life cycle from a single perspective, such as onsite installation (Zhang & Pan, 2020) and manufacturing phase (Dias Barkokebas & Li, 2021); 3) the developed models have limited accessibility, as the participants needed to be in the lab where the experiment was being held. In light of the mentioned limitations, the current study aims to bridge these limitations by developing a VR model that considers all of the implementation phases of modular bridge construction to train practitioners on different OSC processes and connect various project teams. The objectives of this study can be summarized as follows: 1) review the literature contributions in VR-OSC research; 2) develop a framework of a VR model considering the fabrication, installation, and transportation phases of modular bridge construction; 3) test the developed framework on an actual case study on a modular bridge and gather feedback from participants for improvement; 4) develop a cloud platform to support remote access to the model. The rest of the paper is organized as follows: Section Two summarizes the methodology outline, Section Three discusses the model development in the mentioned phases, Section Four discusses the analysis of the model and provides the areas of improvement, and finally, Section Five concludes the current study.

2. METHODOLOGY SECTION

This section demonstrates the methodology and the tools used in this study. Figure 1 outlines the study framework. As mentioned, the proposed framework aims to provide engaging and efficient training for various OSC processes, improve stakeholders' connectivity and coordination, and assist participants in getting familiar with OSC processes. The proposed framework targets many project teams, such as the factory team, onsite assembly team, and transportation team. The developed model in the game engine is further upgraded to be accessible online for project teams.

The framework combines the merits of BIM modeling and game engines. The framework starts with building a 3D BIM model of the modular bridge construction project. The 3D model was developed based on the statistical system of an example of a modular bridge addressed by Xiangmin and Dewei (2021). Autodesk Revit is used in this step to develop the BIM model. An FBX format is used to export the developed BIM model, with all of the needed information and real dimensions, to the game engine tool. In this study, Unity3D is used as the game engine tool. Unity3D has been used by research scholars in developing serious games and VR scenes due to its efficiency and compatibility with technologies, such as BIM (Zhang & Pan, 2021) and hardware sensors (Jeon & Cai, 2021). After the FBX model is imported to the Unity3D platform, the interactions in the virtual scenes are added using C# programming language. The developed virtual scenes include the following: an exploring scene, a transportation scene, a yard scene, and an onsite scene. The scenes will be further detailed in the following section. To facilitate easy access to the developed VR model and leverage the use of the VR model, web cross reality (WebXR) and Web Graphics Library (WebGL) are used. WebXR facilitates the ability to develop fully immersive virtual models across the web using several types of hardware (Bao et al., 2022). A modular construction case study is also discussed to test the proposed methodology, and participants are then asked to evaluate the designed tool, and the feedback is used to improve the development of the model. The following sections will detail the development of each of the discussed steps.

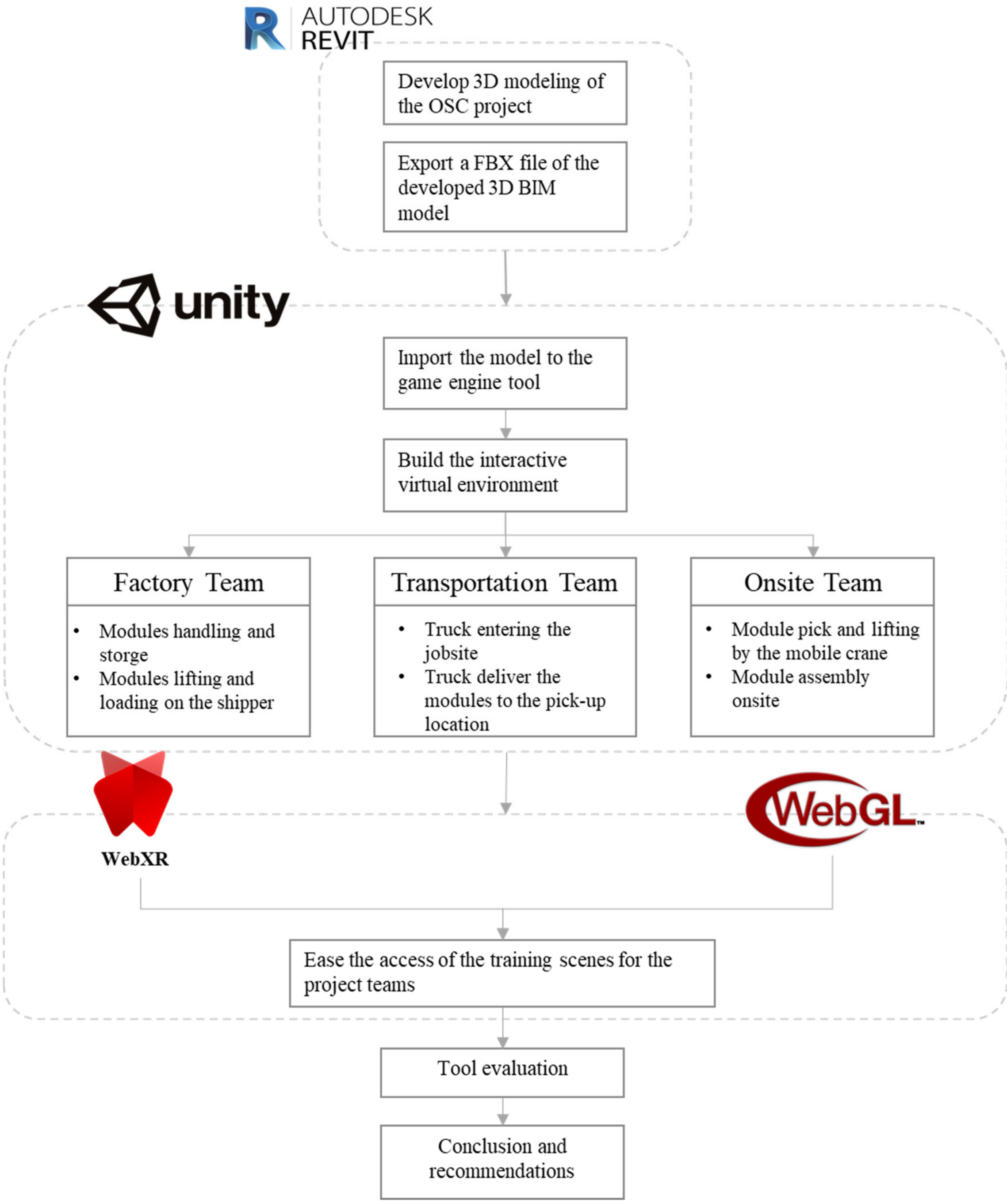

Fig. 1: The study framework

Furthermore, the model testing was performed through two main steps. First, a non-immersive environment is created where the participant can enter any of the developed scenes and test the efficiency of the developed model. This option is valuable when deploying the developed virtual model on the shared cloud. This arrangement allows participants to access the model without the need to have a VR headset and controller. In the second step, the model is then tested in a fully immersive environment. The VR headset and controllers are connected to the virtual model in the Unity3D platform. The controlling buttons are then edited and added to the VR controllers. Participants in the fully immersive model can perform the same tasks using the VR controller. Participants are asked to evaluate the model after the experiment and to provide possible areas of improvement.

Besides the software tools used in the study, a number of hardware tools are also used. The installation of the VR headsets and controllers is shown in Figure 2. The hardware used in this experiment includes the following: 1)

HTC VIVE headset, 2) HTC controllers, and 3) two bases. All of these hardware pieces were connected to the PC and added to the Unity 3D game engine.

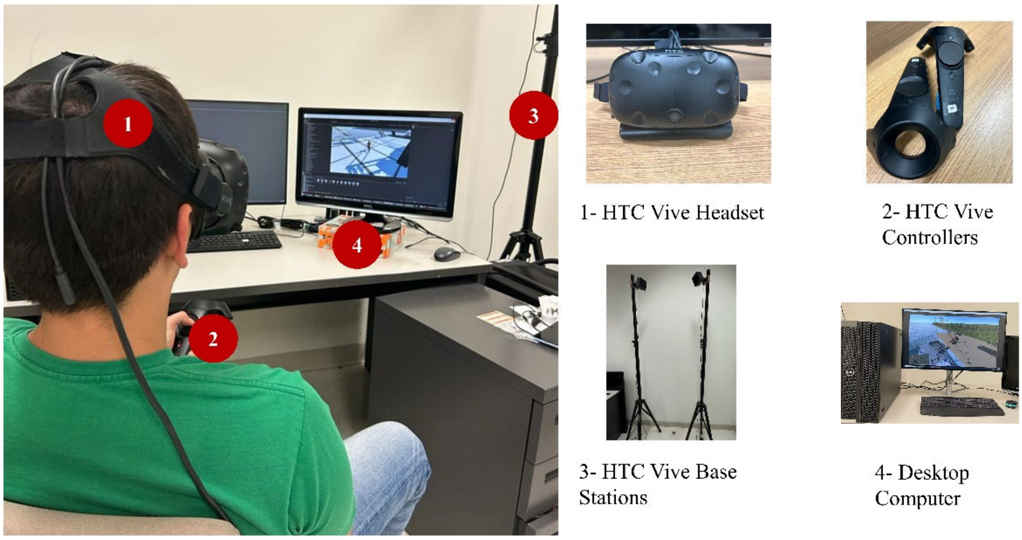

Fig. 2: Hardware used in the VR experience

3. MODEL DEVELOPMENT

In this section, the development of the model is discussed. As mentioned above, Autodesk Revit is used to develop the BIM model, Unity3D is used to develop the virtual interactive scenes, and WebXR is used as the web platform of the model. A case study of a modular bridge is discussed in this section to demonstrate the proposed methodology. It is worth noting that the location, details, and drawings of the case study are remained anonymous.

3.1. BIM model

This section shows the development of the BIM model. The chosen case study comprises the following OSC elements: prefabricated steel modules and precast reinforced concrete slabs. Figure 3 shows the details of the developed BIM model. The shown steel modules are first installed on the bridge, and then the precast slabs are installed on top of the steel modules. The fabrication of the steel modules is beyond the scope of this study. However, handling the steel modules at the factory is included in the developed scenes.

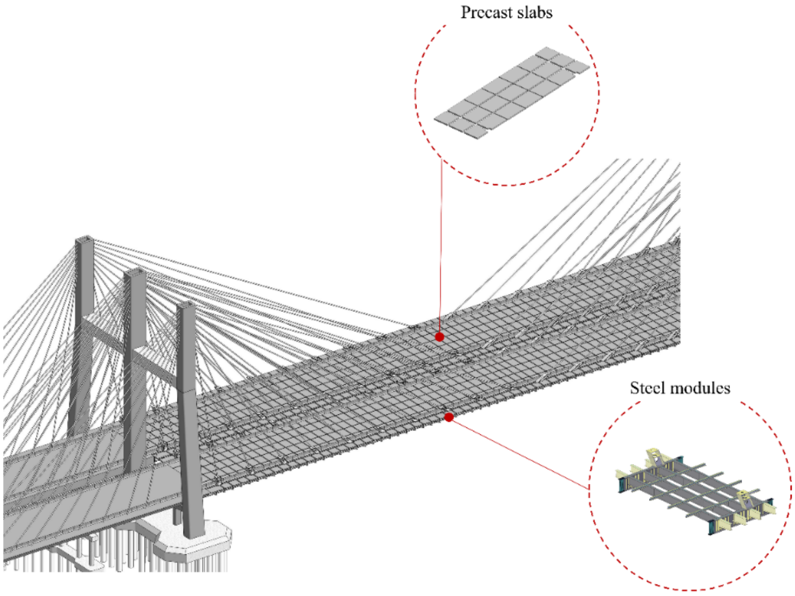

Fig. 3: Developed 3D BIM model.

3.2. Virtual Scenes

This section discusses the development of virtual scenes in this study. The section includes the following scenes: the exploring scene, the yard scene, the onsite scene, and the transportation scene. Further, the graphical user interface (GUI) is used to ease the accessibility of the developed scenes. Figure 4 shows the developed GUI. The user can easily navigate among different choices, including scene selection, scene instructions, and scene options (i.e., audio adjustment).

Fig. 4: GUI of the developed game scenes.

3.2.1. Explore Scene

In the Explore Scene, the participants can walk around the VR model in a fully immersive environment. Figure 5 includes a snapshot of the developed scene. The use of this scene for participants is to get familiar with the project before the actual implementation. In this scene, the location of heavy equipment, material storage, special connections, and safety precautions are included. The participants control a character that moves in the virtual environment to explore the mentioned attributes. Participants can choose different camera views, such as first-person or third-person views. All of the elements in the virtual environment, along with the moving characters, are equipped with colliders, making the experience more realistic. Further, the scene is equipped with sound effects, such as footsteps, to increase the engagement of the participants in the virtual environment.

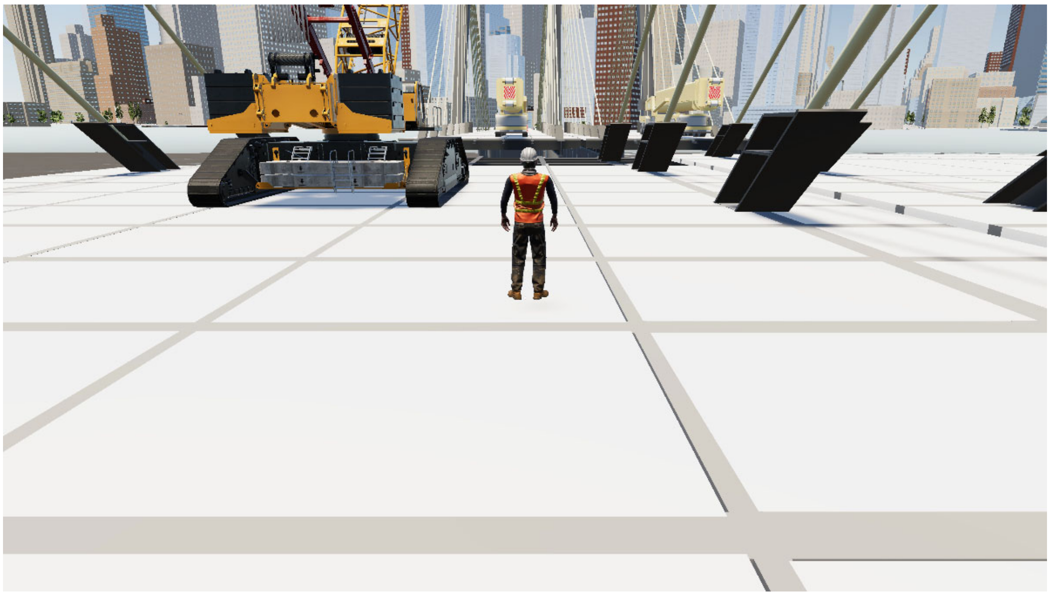

Fig. 5: Exploring scene of the developed model.

3.2.2. Transportation Scene

This scene includes the transportation of the precast slabs to the pickup point. Figure 6 shows a snapshot of the scene. The scene includes the following: a signaler character to guide the truck, signs for the safe entry of the truck, barriers that separate that truck's movement from other vehicles and elements on the job site, and vehicles moving in opposite directions to make the experience more realistic. Furthermore, the sounds of the moving vehicles are also added to the scene for an engaging experience for the participants. In this scene, participants (in this case, truck operators) are expected to drive the truck from the first location to the pickup location. The truck should be able to lift the slabs and assemble them on top of the steel module in the next scene. The scene also shows the clearance of the truck and surrounding elements. The scene then alerts the participant using a beep sound when the clearance is below a certain value. This is achieved through the physical attributes of the elements and collider functions in Unity3D.

Fig. 6: Snapshot of the transportation scene

3.2.3. Onsite Scene

The onsite scene includes the assembly of precast slabs on the steel module. Figure 7 shows a snapshot of the scene. The scene includes heavy equipment, such as a mobile crane, and heavy vehicles, such as trucks. The scene includes many tasks for the participants, such as moving the mobile crane, manipulating the crane boom, tying the module, lifting the precast element, and assembling. The participant (crane operator in this scene) is expected to install the precast slab in the correct location. To make it easier for the participant, an assistant is provided for accurate precast element installation. For instance, a clearance check algorithm is provided so that the participant would know the distance between the element and the nearest surrounding elements. The participant will be notified when this distance goes below a certain value. Furthermore, participants can also enable an option that assists them with the installation process by indicating the projection area on the below elements.

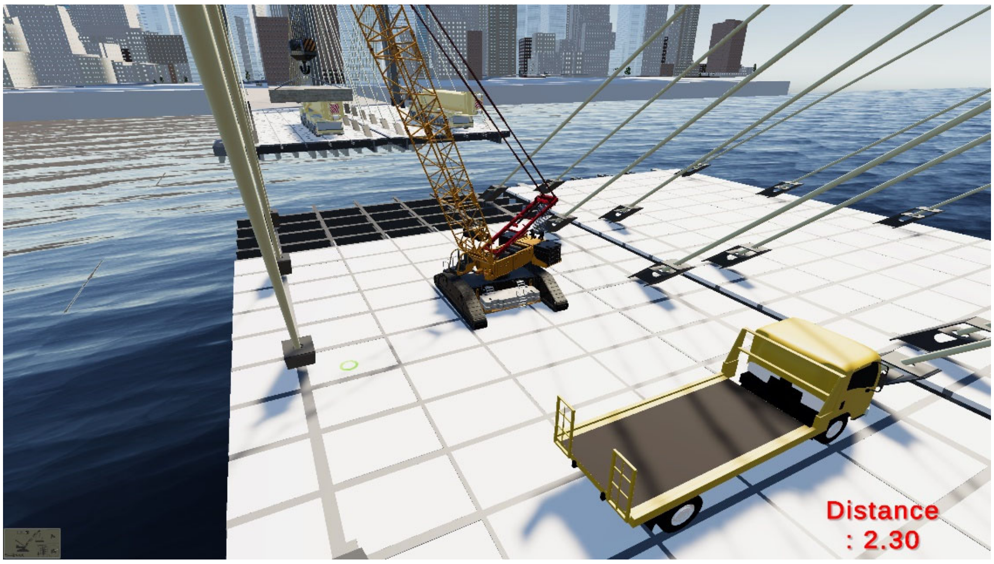

Fig. 7: Snapshot from the onsite scene

3.2.4. Yard Scene

Similar to the onsite scene, this scene targets the handling of the modules in the factory. It is worth noting that in the displayed case study, the factory is represented as a yard where the steel modules were being manufactured. Figure 8 depicts a snapshot of the factory scene. The scene shows how are the steel modules arranged on the yard. The participant is expected to do the same tasks included in the previous scene, but this time with an aim to place the steel module on top of the barge, which later will be shipped to the bridge to be installed. The participant can hook the module and lift it to be aligned on top of the barge. The model provides Various guidelines, such as alerts and the location of the installation. The participant can choose between various points of views, such as the operator view and the barge view. Sounds of the crane engines are also provided to engage the participants in the experiment.

Fig. 8: Yard scene of the virtual model

4. RESULTS AND DISCUSSION

This section discusses the testing of the developed model. A group of researchers from the University of Alberta, where this study was conducted, were invited to test out the developed tool. The testing was performed in both non-immersive and fully immersive environments. In the non-immersive environment, the participant was provided with a demonstration of the keyboard buttons, as shown in Figure 9. The controlling buttons can be adjusted to fit the user preferences. All of the scenes controlling buttons are added in the instructions tab of the developed GUI. The participant should review the controlling button prior to the start of the experiment. On the other hand, in the fully immersive experience, a number of hardware pieces are used, including the VR headset and controllers. As mentioned before, the installation of the hardware is shown in Figure 2. All of the used hardware pieces were connected to the PC and added to the Unity 3D game engine. Further, in the Unity 3D platform, a few add-ons were installed to enable the VR play mode. These add-ons are the XR plugin package and the SteamVR package. The XR plugin package converts the game scene in Unity 3D from regular mode to immersive VR mode after installing the VR headset. In addition, the SteamVR package supports many functions throughout the game scenes, such as teleporting and picking/dropping functions.

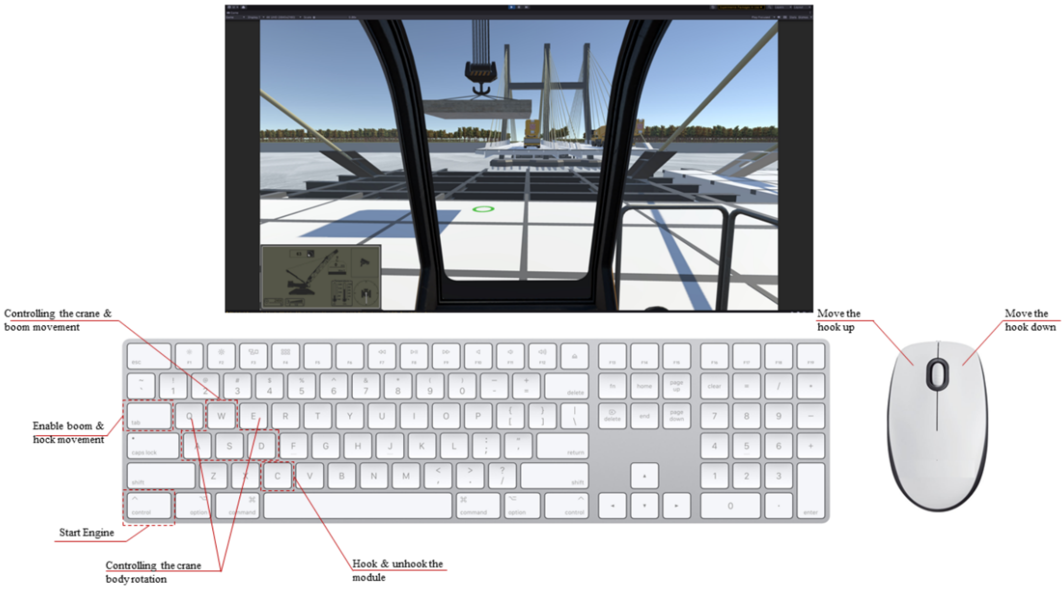

Fig. 9: Instructions of controlling buttons in the developed scenes

Participants were asked to perform tasks in the four discussed scenes. It is worth mentioning that the model was tested using a small sample of VR researchers. The next step in future research is to evaluate the model based on construction and manufacturing professionals' feedback, i.e., workers, truck operators, and crane operators. The tasks that each of the participants needed to complete can be summarized as follows: 1) in the exploring scene, the participant was asked to tour the construction site and identify several elements in the modular bridge, including steel girders, modules, precast slabs, crane locations, and stayed cables. In the immersive reality, the participant controls the movement using the VR controllers and can also teleport easily to different positions with the assistance of teleporting areas and points. When pressing on the VR controller and aiming for a teleporting point, a light is generated in the virtual environment to help the participant navigate to the selected point. This is followed by a list of questions to ensure the participant's understanding of the construction site and factory. The questions range from basic to high-level and detailed questions; 2) in the transportation scene, the participant is asked to drive the truck safely from the starting point to the pickup location. The truck path is determined by barriers and supported by signals, i.e., slow speed signs. Further, participants are also assisted by animated characters, i.e., signalers, that direct them in the right direction. In addition, the participant is also asked to park the truck next to the mobile crane in the specified location; 3) in the onsite scene, several tasks are asked to be performed by the participant. The participant is asked first to turn on the mobile crane engine, move the crane boom, and lower the hook towards the precast slab. Following that, the participant is asked to lift the slab and move to its assembly location. Finally, the participant is asked to install (drop) the slab on top of the steel module; 4) in the yard scene, the participant is asked to perform similar tasks to the previous scene. However, in this scene, the tasks are more complex because of the size of the steel module, which requires more accuracy and precision. The participants are asked for their feedback on the developed model after completing all of the mentioned tasks.

The time spent by the participants in completing the mentioned tasks was 30 minutes on average. Participants reported the high level of immersion experienced and the high level of detail in the virtual environment. It was also reported that sound effects and guidance in the virtual environment have helped participants to be more engaged in the experiment. The participants also reported that the tasks required were clear in the virtual environment and displayed GUI, i.e., clearance check, and module installation assistance facilitated safe and accurate installation. However, participants also highlighted several areas of improvement: 1) the time of the immersive VR was quite long, and participants reported a low level of focus in the last 10 minutes of the experiment (last scene); 2) some of the controlling buttons were hard to follow, especially in the crane scene where the participant needed to control the crane movement, boom rotating, hook movement, and module lifting; 3) the placement of the module was found hard by most participants as it included movement in tight spaces. The collected feedback from participants is used to improve the performance of the developed model. This is part of a continuous study that is currently conducted by the authors. It is also worth noting that the multi-user environment, which enables connections between stakeholders in the VR model, requires further testing by the participants. The cloud application of the model using WebGL and WebXR was also tested. The WebGL plugin was supported by Unity3D. The function of this tool was to build the game scenes in a format that could be deployed online. Figure 10 shows a snapshot of the cloud model. This cloud model was tested across different platforms to ensure its functionality. Furthermore, the model was also supported by the WebXR plugin. This allowed the participants to experience the developed scenes in a fully immersive manner. These tools provide accessibility to the model to multiple stakeholders. The scenes can be easily updated by the designer based on stakeholders' feedback on the cloud platform. It is also worth noting that the authors tested a few scenes of the model due to size restrictions.

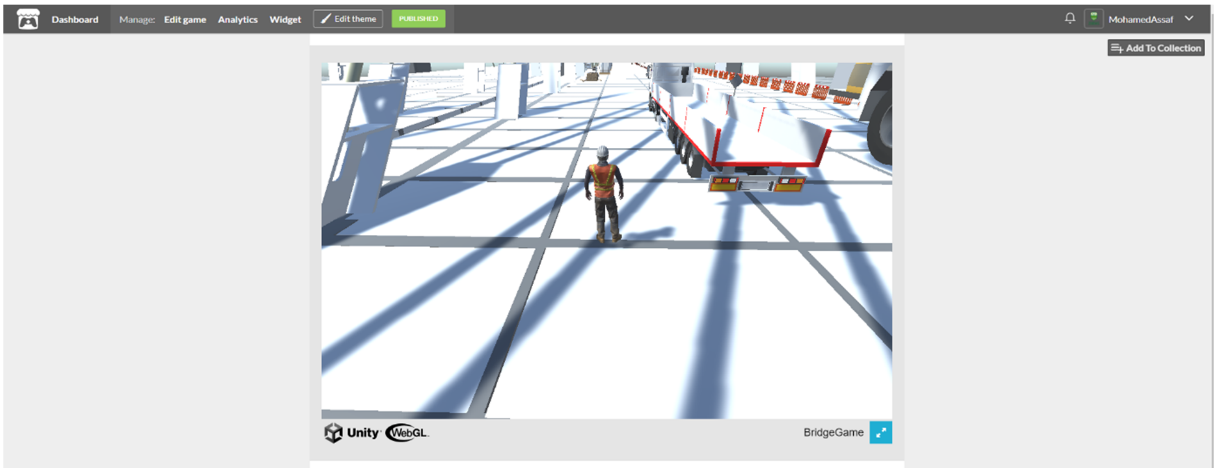

Fig. 10: Cloud platform for the developed model

5. CONCLUSION

This research was motivated by the lack of VR-OSC research when dealing with complex structures, such as modular bridges. Hence, this study contributes by developing a VR model to train participants on the processes included in the construction of modular bridges. The model is supported by a GUI that facilitates the selection of the scene of interest. This includes exploring, yard, transportation, and onsite scenes. The exploring scene allows the participant to walk around the model and explore several elements and connections. In addition, the exploring scene is supported by the steamVR feature that allows participants to navigate among different positions in the scene by pointing the VR controller in the virtual environment to the desired location. In the transportation scene, the participant can maneuver the truck according to a defined path to the pickup point following the road signals and signaler characters. This is supported by sound effects to engage the participant in the VR experience. In the onsite scene, the participant can control the mobile crane to hook the precast slab and place it on top of the steel module. This is also supported by crane and truck sound effects to engage the participant in the experiment. Furthermore, a clearance check between the hooked precast slab and surrounding objects was added to the model. The displayed clearance distance color is turned into red, and a beep sound is played when it goes below threshold to alert the participant. In the yard scene, the participant can control the crane to hook and place the module on the barge. An assistance projection area is displayed to help the participant in placing the module in the correct location on the barge.

The results show the capability of the model to immerse participants in the VR environment. Furthermore, they also showed participants' understanding of the processes through hands-on experience. However, the feedback from the participants showed a lot of areas of improvement, including the duration of the experience and the complexity of controlling the crane in the crane scenes. These areas of improvement are considered future research directions for the current study. The study provides theoretical and practical contributions. Theoretically, the study is considered a basis for a collaborative VR model that can facilitate process planning in OSC projects. Practically, the study provides an advanced VR model that can be used to connect and train OSC practitioners on various processes. Despite the contributions provided by the study, several limitations are included. The sample of participants is considered small compared to the scale of the study. However, this paper is considered a first step in continuous research that explores VR in OSC projects. Furthermore, the study theoretically explores the potential of the WebXR feature that allows easy access to the model. Future studies will be conducted to create access control for the developed model on the WebXR. In addition, the next step in this research will target the use of wearable sensors, such as eye-tracking sensors, to mitigate subjective feedback by the participants.

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