INTEGRATION OF BIM DATA AND REAL-TIME GAME ENGINE APPLICATIONS: CASE STUDIES IN CONSTRUCTION SAFETY MANAGEMENT

Ahmad Akib Uz Zaman

Department of Civil and Architectural Engineering and Construction Management, University of Wyoming, Laramie, WY 82071, United States

ORCID: 0000-0003-1495-4780

azaman@uwyo.edu

Ahmed Abdelaty, PhD

Department of Civil and Architectural Engineering and Construction Management, University of Wyoming, Laramie, WY 82071, United States

ORCID: 0000-0001-7329-452X

*aahmed3@uwyo.edu (*corresponding author)*

Md. Habibur Rahman Sobuz, PhD

Dept. of Building Engineering and Construction Management, Khulna University of Engineering and Technology, Khulna 9203, Bangladesh

ORCID: 0000-0002-6279-5406

habib@becm.kuet.ac.bd

SUMMARY: Building Information Modeling (BIM) has unique features that improve safety management in construction by visually identifying potential risks. Integrating BIM with a real-time game engine is a cutting-edge idea for more effective safety management. This study aims to conduct two case studies by integrating BIM data with game engines from two aspects: 1) Construction Safety Training and 2) Pre-construction Safety Management. A framework that covers techniques for extraction of safety ideas, managing the game engine, and character modeling tools and resources is used to carry out the case studies. In the first case study, a construction site was created by Revit, and a real-life scaffolding failure accident was simulated by Unity to warn workers to prevent similar future events. The second case study was conducted on the procedure of evacuation modeling in an emergency, integrating a BIM model and Unity following distinct pathways. This evacuation modeling can be used as a training platform for the occupants to acquaint themselves with the inside facility, show directions of the shortest evacuation path from specific points, and provide necessary information on emergency equipment. Finally, the study explains how the integration of the BIM model and game engine applications can be applied for effective, straightforward, and helpful safety management with the most efficient BIM data transition.

KEYWORDS: Building Information Modeling (BIM), Game Engine, Construction Safety, Accident Simulation, Evacuation Modeling.

1. INTRODUCTION

The primary goal of any construction project is completing the project according to the design and specification, within budget and timeframe, and without any casualties. However, the construction industry is considered one of the accident-prone areas where many fatal and nonfatal injuries happen every day worldwide. In the USA, 4,764 workers died due to work-related accidents in 2020, where 1,008 fatalities, or 21.2 percent of all fatalities over that period, were related to the private construction business (BLS, 2022). The number of deaths was the highest in the construction sector that year, where transportation and warehousing industry deaths were second with 805 fatalities. Generally, two main factors are vital in causing accidents at construction sites. One is the worker's actions, and the other is the site condition. It is tough to predict which factor may lead over another in a construction site because each site is unique from its perspective. However, some common accidents have occurred over the years, and the root causes must be investigated and analyzed. Here, traditional methods of investigation and analysis can be done virtually with simulation effectively and efficiently.

There are two categories of construction safety management: pre-construction and construction phases (Zhang et al., 2014). Potential safety hazards are typically recognized during pre-construction based on the experience of the safety personnel and eliminated through safety planning and training (Guo et al., 2017). So, the identified root causes of accidents and the potentially hazardous site conditions can be present to the workers and supervisors through pre-construction safety management. Also, safety training is required during the construction phase as the site is ever-changing, and many unwanted hazardous conditions may arise in different stages. However, safety training is generally based on classroom instruction, which lacks interaction, intuition, and hands-on training and does nothing to raise workers' awareness of safety (Cheng et al., 2004). Also, numerous studies have alleged that traditional safety training methods may lead to low involvement among construction workers, impeding the transfer of knowledge during the training process (M. Zhang et al., 2022).

Therefore, interactive safety training sessions would be more effective with the workers' virtual exploration of the construction site so that they can deeply understand the potential safety risks, accidents, and hazardous site conditions. Moreover, the simulation of accidents in the game created for the training would help investigate and analyze the root causes of the accident. As a result, safety supervisors and workers will be more concerned about the potential dangers, work carefully, prevent accidents before they occur, and avoid hazardous site areas.

According to Borrmann et al. (2018), a building information model is an extensive digital depiction of a constructed facility that has a high degree of detail and usually includes the three-dimensional geometry of the structure's component parts. Consequently, the creation of these digital building models, as well as their use, upkeep, and exchange during the physical facility's existence, are collectively referred to as Building Information Modeling (BIM). The architecture, engineering, and construction (AEC) and facilities management industries are increasingly implementing BIM, changing how safety might be tackled (Zhang et al., 2013). Besides planning, design, and construction, BIM opened a new era of safety management. In the field of engineering and management, BIM is an emerging technology that manages the connections between design and safety on site (Kamardeen, 2010). Hazard identification and recognition, safety training and education, and fall prevention planning are among many safety criteria that are being implemented with BIM (Marefat et al., 2018).

However, BIM itself has some limitations in immersive visualization and interactivity, which game engines can complement (Park and Kim, 2013). It has been demonstrated that game engines can address these limitations by boosting immersion and enhancing comprehension of real-world situations, and can also be used to supplement in-person safety training (Afzal et al., 2021). Integrating BIM and the game engine can refine the visual experience of potential accidents, hazardous areas, and interactive hazards or accident prevention procedures. Some research has been conducted integrating BIM and games for construction safety purposes such as safety planning (Azhar, 2017), fire safety (Chen et al., 2021a), and safety training (Afzal and Shafiq, 2021 and Bao et al., 2022).

However, more areas need to be explored, such as where BIM data can be integrated with game engines to find the optimum potential for construction safety management enhancement. Additionally, the effectiveness of this integration and the final developed games must be validated by Civil Engineering and construction-related personnel. That is how it can be ensured that the safety games can impact the real field in improving construction safety. On the other hand, there are different pathways with several data formats to integrate these two different platforms; however, not all pathways are equally efficient. There is a need to investigate discrepancies between different pathways and find the most efficient one.

Therefore, the primary objective of this paper is to conduct two case studies by integrating BIM data with game engines from two aspects: 1) Construction Safety Training and 2) Pre-construction Safety Management utilizing a

framework. The framework comprises two modules focused on construction safety, which aim to develop safety training materials and pre-construction safety management concepts. They facilitate the integration of this information into existing (BIM) models or aid in creating new models based on extracted data. The two case studies are chosen based on these modules. Also, in the framework, two different ways of integrating BIM data and a game engine with various file formats are shown, and each case study proceeds along a different path. Furthermore, this study discusses the issues raised for specific pathways and recommendations for effective and efficient BIM data and game engine integration. Moreover, the ways of handling the game engine for two safety conditions, interactivities, and character modeling tools and sources are discussed. In the first case study, a construction site is created by Revit, and a real-life scaffolding failure accident is simulated by the game engine Unity in order to alert workers to avoid similar incidents in the future. Also, the workers could identify the root cause of the accident while virtual exploration of the site. The second case study demonstrates emergency evacuation modeling and procedure by fusing a realistic BIM model with Unity and using different pathways. Additionally, the study aims to validate the built games from the case studies via user testing and evaluation to understand how effectively the games can enhance real-life construction safety management.

The first case study will assist the safety associates in simulating any construction accident and train construction workers so that they will be able to avoid any potential accidents during construction, as well as increase productivity at the construction site. Also, with the virtual exploration of the post-construction accident area, the workers can scrutinize the accident's root cause, which could serve as an example of a new approach to accident investigation. Finally, the second case study will help create evacuation models during emergencies and check the adequate number of exits for any facility in the pre-construction phase. Developing an emergency evacuation model utilizing the BIM model and game engine as pre-construction safety management strategies will benefit the construction industry by effectively managing hazardous situations.

2. BACKGROUND AND LITERATURE REVIEW

The background and literature review section extensively discusses BIM's benefits for construction safety and its evolving integration with game engines for immersive visualization and interaction. Subsequently, it explores research on their combined applications and highlights their promising role in enhancing construction safety initiatives.

2.1 BIM

According to international standards, BIM is a shared depiction of physical and functional qualities in the digital form of any built object that constitutes a trustworthy foundation for decisions (Hjelseth, 2010). Instead of the two-dimensional (2D) structure representation typically shown in computer-aided design (CAD) drawings, a BIM model contains the building's accurate assemblies (Krygiel and Nies, 2008). Many benefits have been found in using BIM over conventional techniques (Barlish and Sullivan, 2012); however, the construction industries in many countries are slowly adopting this technology (Mehran, 2016; Seed, 2015; and Masood et al., 2014). Project collaboration is one of BIM's key benefits that must be promoted to increase this adaptation rate. The foundation of collaboration is information sharing, which necessitates that software be able to interchange data across stakeholders and data formats (Afsari et al., 2016).

Therefore, several BIM data-sharing formats have been developed, e.g., industry foundation classes (IFCs) (Lai et al., 2019) and Filmbox (FBX) (Khalili, 2021). Utilizing these BIM data exchange formats, users can transmit design data and specifications between multiple software applications within an organization and, more specifically, in a multidisciplinary team. Any data revisions required during the design phase may be handled systematically and preserved throughout the project life cycle since BIM stores the data as a database (Ghaffarianhoseini et al., 2017). Also, the building component data sets are distinctively recognizable, along with various operational and informative metadata (Tang et al., 2019).

2.2 BIM and construction safety

BIM tools can potentially improve construction safety by using the model information in the planning, designing, construction, and post-construction phases. Additionally, BIM can increase worker safety by enabling architects, engineers, and contractors to visually examine job site conditions and identify potential risks before construction begins (Azhar, 2017). It offers a platform that other BIM-based development can use to integrate external data with the parametric BIM environment and carry out additional automatic risk analysis in the design of buildings,

which can aid architects and designers in making quicker decisions about or improving alternative designs (Nizam et al., 2018).

Prevention through design is a concept that researchers are continually studying to reduce accidents on the site and identify hazardous conditions. Two key themes have emerged to achieve prevention through design: employing BIM software for conflict detection and combining BIM and knowledge-based systems to identify safety hazards (Yuan et al., 2019). To automatically detect potential safety issues throughout the design stage, Hongling et al. (2016) coupled BIM with design safety guidelines. In the research of Zhang et al. (2013), a rule-based automated checking system for BIM is developed, and the discussion of how future safety planning can be incorporated into project schedules and work breakdown structures is discussed.

The further research of Zhang et al. (2015) creates an automated BIM-based fall threat identifying and planning tool that interactively indicates possible fall hazards based on the construction schedule, strongly supports labor-intensive modeling and planning tasks of fall prevention systems and increases workers' awareness by depicting the possible dangers. Also, crane safety is a major issue on the construction site. Operators and managers can more easily and precisely analyze potential conflict elements and identify unrealistic lift plans with the help of 4D-BIM models, preventing casualties and injuries brought on by crane collisions (Chatzimichailidou and Ma, 2022). On the other hand, Shen and Marks (2016) developed a framework for gathering and visualizing near-miss data in a construction site on a BIM platform. An easily obtainable BIM design application established a near-miss database so construction site workers might report near misses and visualize within an existing BIM model.

Some BIM-based applications are applied in actual construction projects to improve safety. For example, Sulankivi and Kiviniemi (2010) investigated the potential for 4D-BIM as the primary technology for safety-related planning activities and ongoing research-building projects called BIM Safety. Their study showed how BIM software might be employed to carry out planning tasks for safety-related planning and four-dimensional site layout. Moreover, BIM has prospects for automated safety checking (Hossain and Ahmed, 2022), fall hazard identification (Tözer et al., 2024), and emergency evacuation (Y. Tang et al., 2021).

2.3 Game engine

Without referring to specific engine parts, game engine definitions are frequently quite general and ambiguous, such as "a framework made up of a variety of different tools, utilities, and interfaces that conceal the low-level specifics of the numerous activities that make up a video game" (Sherrod, 2006). However, Lewis and Jacobson (2002) have given a more solid definition. According to them, the group of simulation code modules that do not explicitly specify the game's behavior (game logic) or environment is called the game's engine (level data). The engine's modules handle input, output (including 3D rendering, 2D artwork, and sound), and general physics/dynamics for game environments. Currently, several game engines are on the market, such as Unity, Unreal Engine, Godot, and Cryengine.

Game engines are incorporated with all physics laws, and interactivities can be added with code scripts. It is vital in creating VR and AR. VR completely immerses users in a virtual world with few real-world objects and scenarios; however, with augmented reality, users can interact with real objects to some extent even though they are not fully immersed in a virtual world (Babalola et al., 2023). Also, the engines have top-notch rendering qualities, so realistic visualization makes them more appealing to users. This broad range of applications is explained by VR's capacity to combine the realistic recreation of a virtual environment with the chance for the user to interact with the environment itself (Scorpio et al., 2022). In addition to immersive visualization capabilities, game engines can produce valuable synthetic data, facilitating the simulation of various construction scenarios from various angles (Lee et al., 2023). However, Chien (2002) asserted that designing is quite comparable to playing a game: both involve exploring options while being subject to limitations. It is challenging to construct construction or build a model in the game engine from scratch.

On the other hand, data sharing between 3D modeling software and game engine applications is one of the most crucial elements; however, some interoperability issues have been found among these software applications (Khalili, 2021). Architects or design professionals may find difficulties importing and exporting CAD files into the game engine (Lehtinen, 2002). Sallkachat and Choutgrajank (2003) proposed making tools that would allow CAD software files to be imported into a game environment. Also, Petzold and Frohburg (2006) recommended that research must concentrate on approaches for streamlining the available software and modifying it to meet the requirements of architects. Therefore, extensive research is being conducted to mitigate the interoperability issues, and different ways of integration between game engines and BIM have been developed (Zheng et al., 2023, and

Nandavar et al., 2018). Though BIM tools have their own visualization capabilities for adding interactivity, making the model dynamic, building VR and AR platforms, and going for extensive visualization, the game engine is a suitable option for integrating BIM data (Buhammood et al., 2020). Therefore, the interoperability between two different platforms by the developed procedures with different file formats must be tested to investigate the effectiveness of this interoperability. In the process of investigating various integration techniques, several concerns may also come up, all of which need to be looked at further in order to achieve the best possible interoperability.

2.4 BIM and game engine

One of the latest endeavors for BIM is to integrate with the game engine for various applications in the construction sector, such as collaborative decision-making (Du et al., 2018), interactive design change (Panya et al., 2023), and construction project monitoring (Pour Rahimian et al., 2020). Ratajczak et al. (2019) proposed a working prototype of augmented reality for construction (AR4C). This BIM-based AR application combines with a location-based management system (LMBS) to enhance the efficiency of construction projects.

As the primary development environment in this research, Unity, a game engine, was used to create a prototype of the AR4C application. Various applications had to be connected, and multiple data had to be exchanged to make it possible to visualize the 3D model and information related to construction jobs. Two files were exported from Autodesk Revit: a 3D model via a .fbx file format and its metadata via a .xml file with a plugin. The .fbx file format was first imported into Autodesk 3ds Max to handle the model organization by entities and retain the identical IDs of 3D objects in Unity and Autodesk Revit. The geometry was loaded into Unity straight after being exported in the .fbx file format. Boeykens et al. (2011) integrated game engines, such as Unity and Unreal editor, and the BIM model created by SketchUp, ArchiCAD, etc., to recreate historic buildings and mimic scenes in their case studies. Also, Boeykens (2013) showed how Unity can be used for architectural visualization. Moreover, Yan et al. (2011), Albourae et al. (2017), Oerter et al. (2014), and Bille et al. (2014) integrated the BIM model with game engines, especially for visualization purposes. Albourae et al. (2017) created a database of the 3D objects' components using the BIM software platform Revit after extracting a 3D model from the image-based, range-based, CAD modeling, and land survey approaches. The BIM model was then integrated with Unity, enabling the user to use mobile devices to interact with the environment.

In addition, to connect the design, production, transportation, and construction teams working on a project utilizing a single digital platform, a game engine-based digital platform was established by Ezzeddine and García de Soto (2021). For interactive life cycle cost (LCC) analysis, Omaran et al. (2019) discussed the interoperability of the game engine and used LCC analysis to improve visualization and instruction. A BIM-game prototype was developed that combined BIM with a Unity simulation running in real-time to provide an LCC analysis visualization. With the capacity to simulate the LCC, the BIM-game prototype allowed users to navigate their building settings. In addition, Wang et al. (2014a) integrated the BIM tool Revit as a comprehensive building information source with Unity to create an immersive gaming environment for real-time fire evacuation guidance.

For improving construction safety, Hongling et al. (2016) developed a specialized test platform by fusing Autodesk Revit and Unity 3D to show the viability and validity of the BIM-safety rule-integrated approach to identify risky design issues automatically. Also, Chen et al. (2021) provided a novel technology-integrated framework for developing a BIM, Internet of Things (IoT), augmented reality, and virtual reality system proof-of-concept based on the theory of situational awareness. Moreover, in the research of Zhao and Lucas (2015) created 3D object models and a 3D environment for simulation construction safety training using a modeling tool and a gaming engine. The training concentrated on testing employees who could benefit from lowering the number of electrocution-related mishaps and fatalities. The results showed that the VR-based safety training program can provide a secure work environment where users can practice tasks that involve electrical risks and eventually improve their cognitive and interventional skills related to electrical hazards.

From this background section, it can be observed that BIM and game engine integration have been applied in many AEC areas. However, little research has been conducted for construction safety purposes, and many benefits are yet to be explored. The primary purpose of taking safety actions or management is to reduce the number of accidents. One of the leading causes of the accident is working at a height, e.g., scaffolding work at the construction site (Abas et al., 2020).

Clevenger et al. (2015) examined and evaluated the creation of a scaffold safety training module with interactive, BIM-enabled 3D representations to see if such a tool might improve scaffold safety training. However, this type

of safety training module can be enriched with the real-life scaffolding accident scene simulation, which helps the workers and safety associates visualize and understand the root causes of the accident. Therefore, the first case study of the paper focuses on simulating a real scaffolding accident utilizing a BIM model and a game engine, and the game aligns with the research of Clevenger et al. (2015).

Moreover, in the pre-construction phase, evacuation modeling is vital to check the developed model's capabilities to evacuate the building occupants in short periods of time with an adequate number of exits and showing important safety features such as proper area labeling and fire extinguishers. Integrating BIM model data and the game engine can create the modeling as a training platform for the end users. Rüppel and Schatz (2011) introduced a simulation for human rescue utilizing BIM for fire emergencies. Also, Wang et al. (2014b) utilized BIM and game engine technologies to improve building management during fire emergencies by creating a virtual environment for the users.

In addition, Liu et al. (2014) examined the prospect of combining BIM, immersive games, online games, socio-psychology, and physics models to solicit and gather authentic human responses in various emergency circumstances. The VR experiment conducted by Zhao et al. (2022) revealed that this kind of system can lessen participant stress, increase the effectiveness of evacuation, and lessen the amount of damage caused by the fire. Hence, other scholars have established the prospect of using BIM and game engines for emergency evacuation. Therefore, the second case study in the paper focuses on how well BIM data can be integrated with a game engine to produce an evacuation model for a real facility for any emergency, as well as an instructional tool for end users. Therefore, the second case study in the paper focuses on how well BIM data can be integrated with a game engine to produce an evacuation model for a real facility for any emergency, as well as an instructional tool for end users.

3. METHODOLOGY

A framework demonstrating the process of merging game engine data with BIM data has been established to carry out the case studies. This framework includes idea and information modules of construction safety, BIM tools, several transition processes, a game engine incorporating an interactivity process, and character modeling tools/source integration and build strategy. This developed framework shows two different ways of creating end-built platforms for two case studies utilizing different file formats for construction supervisors, workers, or users to be trained or get information regarding safety issues from two different safety management aspects. Revit is considered the BIM modeling tool in this framework, and subsequently, 3ds Max has been used as a transition tool. SketchUp has also been used as an optional 3D modeling tool to create 3D construction model elements according to safety ideas and information and integrate the elements with BIM models in BIM tools.

In addition, as a game engine, Unity is considered for simulation and building the final model on different platforms. Furthermore, it is essential to use C# code to add interactivity, so Visual Studio is used for coding, and the (.cs) files are integrated with different parts of the Unity model. Moreover, Mixamo, Blender, and Unity Asset Store are considered sources of human characters in this framework. Finally, six different platforms are shown in the framework on which the safety associates, supervisors, and workers can get access to explore from their convenient devices.

3.1 Developed framework for case studies

The framework, depicted in Figure 1, is divided into several components:

(1) Data Exchange Formats; (2) Idea and information generation, BIM model checking, and transition of the information to the BIM model; (3) Utilizing BIM and 3D Modeling Tools; (4) Transition Tools; and (5) Working with Game Engines and Character Modelling Tools/Sources.

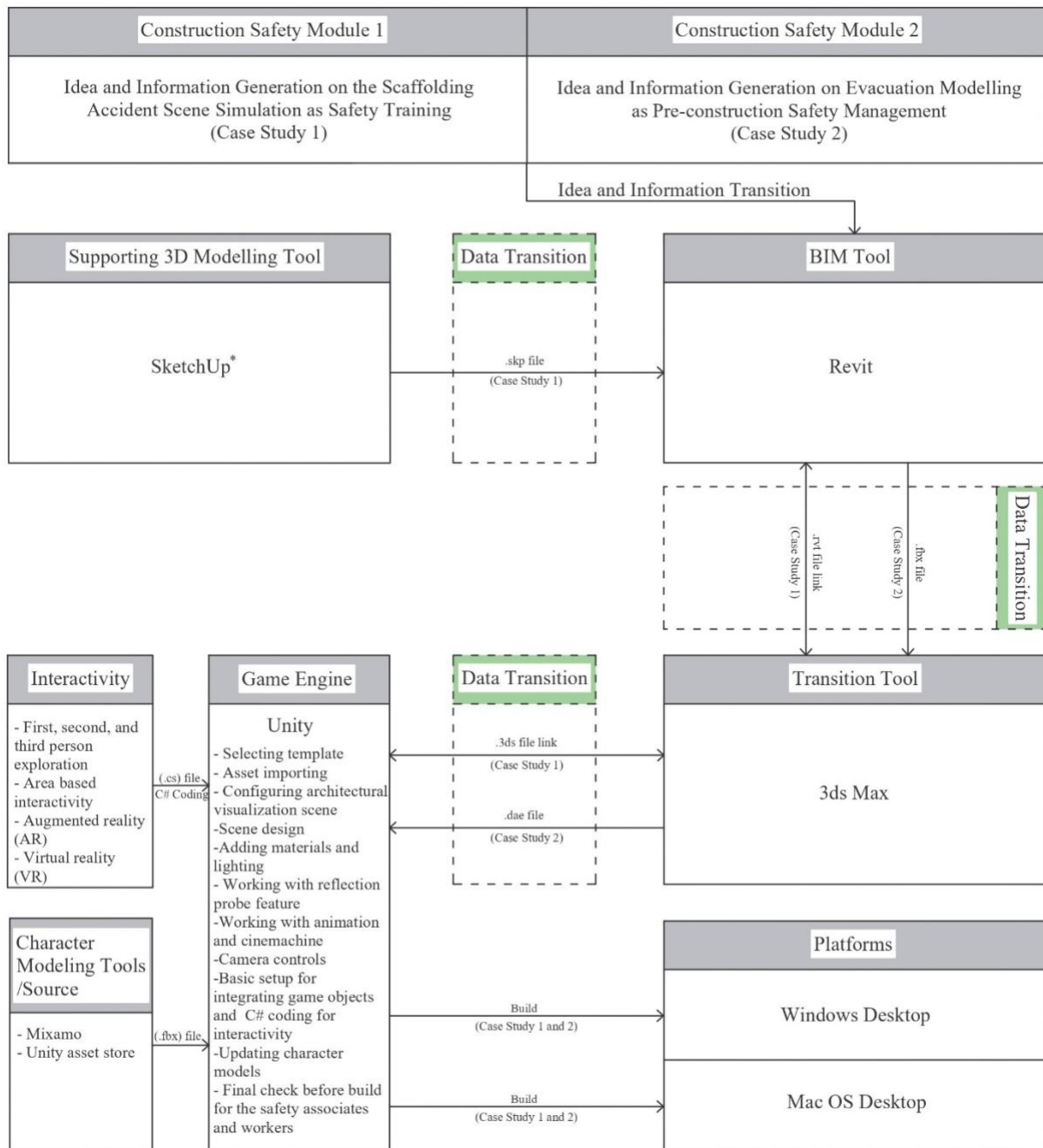Each component is described comprehensively in this methodology section.

Construction Safety Module 1

Idea and Information Generation on the Scaffolding Accident Scene Simulation as Safety Training (Case Study 1)

Construction Safety Module 2

Idea and Information Generation on Evacuation Modelling as Pre-construction Safety Management (Case Study 2)

Idea and Information Transition

Supporting 3D Modelling Tool

SketchUp*

Data Transition

.skp file (Case Study 1)

BIM Tool

Revit

Data Transition

.rvt file link (Case Study 1)

.fbx file (Case Study 2)

Interactivity

- First, second, and third person exploration
- Area based interactivity
- Augmented reality (AR)
- Virtual reality (VR)

Game Engine

Unity

- Selecting template
- Asset importing
- Configuring architectural visualization scene
- Scene design
- Adding materials and lighting
- Working with reflection probe feature
- Working with animation and cinemachine
- Camera controls
- Basic setup for integrating game objects and C# coding for interactivity
- Updating character models
- Final check before build for the safety associates and workers

(.cs) file C# Coding

Data Transition

.3ds file link (Case Study 1)

.dae file (Case Study 2)

Transition Tool

3ds Max

Character Modeling Tools /Source

- Mixamo
- Unity asset store

(.fbx) file

Platforms

Build (Case Study 1 and 2)

Windows Desktop

Build (Case Study 1 and 2)

Mac OS Desktop

Figure 1: Framework to integrate BIM data and game engine for two case studies from two construction safety aspects.

3.2 Data exchange formats

BIM data sharing is essential for seamless operation and interoperability across different platforms that require specific file formats. In the framework (shown in Figure 1), .fbx and .dae, along with proprietary file formats (.skp, .rvt, and .3ds), are used to conduct case studies. Exporting BIM data as proprietary files by another platform's applications becomes a little more complicated. For example, native files such as Revit or SketchUp cannot be directly imported by Unity. However, SketchUp files can be directly imported by Revit, and then Revit data or models can be directly linked to 3ds Max, and 3ds Max files can be directly imported into Unity. However, a significant challenge in exporting BIM to Unity with different data exchange formats is the high number of

polygons and vertices in the resulting model. This issue can be resolved with different strategies. One method is BIM model mesh optimization, as shown in the research of Pa et al. (2022). Also, utilizing prefabs in Unity after importing the data exchange files. Prefabs are game objects that are already configured and can be used as templates to build new instances of items in the scene tab, which optimizes models in the game engine. Another useful option for improving performance in Unity while using 3D models is the occlusion culling technique. Occlusion culling is the process of not rendering areas of a scene that are not visible to the player during runtime, therefore reducing the amount of processing power needed to render the scene (Svensson, 2016). By using this technique, the amount of geometry that is designed for each frame is reduced, which permits an improvement in efficiency and GPU performance (Koulaxidis and Xinogalos, 2022). In our case studies, both prefabs and occlusion culling techniques are used for better optimization.

3.2.1 FBX

FBX (.fbx file) is a widely supported 3D model and animation data exchange format. Because .fbx is so solid and adaptable, it will likely continue to be the most commonly used 3D export format for many years (Ardolino et al., 2014). Revit can easily export .fbx files, and Unity can import them and vice-versa. However, it is a problem that the way Revit exports a .fbx file is not entirely readable by Unity. So, there is a possibility that some information is lost when exchanging data this way. In this case, the exported .fbx file from Revit should first be imported into the third-party modeling application 3ds Max and then exported as a new .fbx file. This .fbx file is fully readable by the game engine Unity. The model can also be exported in .fbx file format if it is created using Sketchup Pro.

3.2.2 COLLADA

The COLLADA (.dae file) data format, which is based on the XML database schema and was created to transport 3D asset data across programs, may be easily expanded to contain extra information about the many features of 3D virtual objects used in VR applications (Miyahara and Okada, 2010). The intermediate language offers thorough visual scene encoding that considers geometry, shaders and effects, physics, animation, kinematics, and even various version representations of the same item (Khronos, 2011). The .dae file format uses the .dae extension, which stands for "digital asset exchange," and is interoperable with many applications. Revit does not directly export the model in .dae file format. However, there are some plug-ins available to export Revit models in .dae file formats, such as Lumion LiveSync (Lumion, 2024). On the other hand, 3ds Max and SketchUp can export the model in this format directly, which can be imported directly to Unity.

3.3 Idea generation, BIM model checking, and information transition

It is essential to choose the relevant case studies in an organized manner. For this reason, the developed framework incorporates two modules on two safety aspects: pre-construction safety management and construction safety training. These two modules help generate ideas and information, check the BIM model's eligibility for conducting case studies, and transfer the information to the BIM model. Based on the ideas and information extracted from the modules, the BIM model would be created from scratch, updated to the existing one, or incorporated components from other sources for further integration with other platforms.

3.3.1 Module 1: Generating ideas and information from the construction safety training aspect

An essential variable affecting how construction workers behave and their safety is their capacity to recognize and evaluate dangers, which they develop via training and experience (Sacks et al., 2013). Safety training is vital to reduce the number of accidents on site, and determining which training should be provided to the workers and safety supervisors is essential. Therefore, this module (shown in Figure 2) will not only help for case study 1 but also assist safety associates in generating and transferring specific construction safety training ideas and information to the BIM model for further integration.

Construction safety training can be of two types: independent or project-specific. Only the independent training portion is considered in this module (shown in Figure 2). Next, it is required to generate and select the independent training idea, and there are many ways to generate and select it, such as specific training needs and analysis of the accidents that frequently occur. For case study 1, the training idea generation and selection were based on the literature review. After generating an idea and selecting specific training for the case study, the training requirements, such as the BIM model's training location, different 3D components, and human characters animation, need to be determined. Again, these requirements can come from different sources, e.g., previous or similar training, safety associate's own instinct, and real accident incidents. Case study 1 of the paper gets the requirements from a real scaffolding accident scene found on an online video.
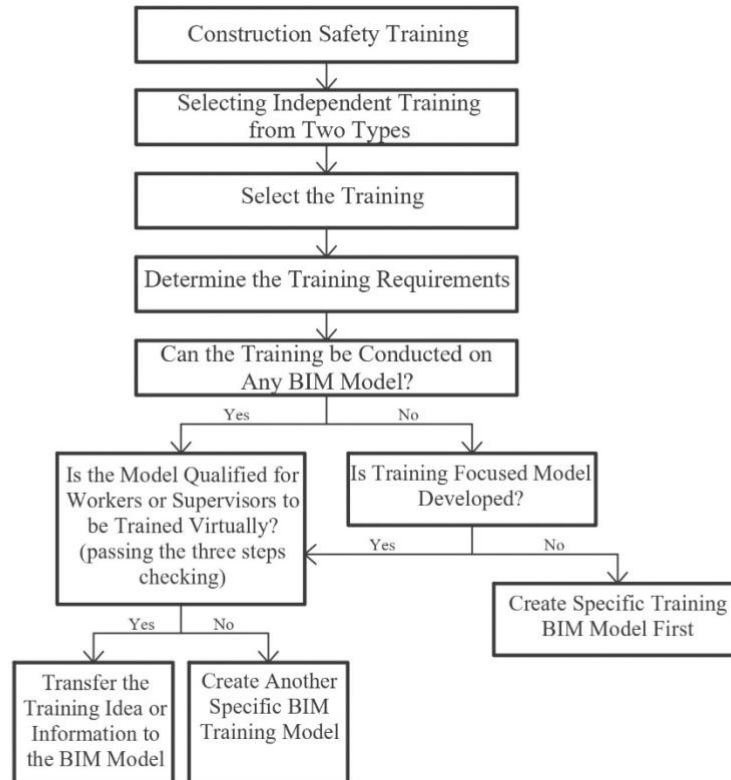
Figure 2: Flowchart of module 1 for generating information from the construction safety training aspect, checking the BIM model's eligibility, and transferring information to the BIM model.

After determining the training requirements, it needs to be assessed whether the training can be conducted on any BIM model or not. For example, if the training focuses on wearing PPE for the workers, such as helmets, safety vests, etc., then any BIM model can be used where the model characters can be integrated later. On the other hand, a specific BIM model is required to train on common accidents, such as falling from height during construction. Not every BIM model shows the construction phase and has adequate heightened space for falling hazards. Therefore, a training-focused model is required if the selected training cannot be conducted on any BIM model.

Three checks need to be performed to determine if the independent training can be carried out on any BIM model. First, it needs to be confirmed that the BIM model can fulfill the purpose of the training. If the model and the training purposes are totally different, the model will not be eligible for further integration. For example, a complete building BIM model cannot be used for training that is related to scaffolding accident prevention during construction. Second, it should be verified that the BIM model is editable. It will not be possible to add more components for a particular training if the user cannot edit the model. Third, it must be ensured that the BIM model can be converted into proper file formats without broken or missing model elements or data to integrate other platforms, as shown in Figure 1.

3.3.2 Module 2: Generating ideas and information from the pre-construction safety management aspect

Assessing the project risks and proactive safety actions in the pre-construction phase can reduce the number of fatal or nonfatal accidents in the construction phase. Generally, the pre-construction safety management tasks are done in the corporate office, and with the BIM model, the safety management tasks can be more effective. However, generating the types of safety action information and importing that into the eligible BIM model is essential. Hence, this module (shown in Figure 3) will help generate safety action information on pre-construction safety management, check the eligibility of the BIM model, and transfer the information to the model for case study 2 for further integration.

There are different types of pre-construction safety management for a project; however, building emergency safety management is considered for this case study based on its importance, as found in the literature review. If

managerial actions are taken on building emergencies before construction, it can help reduce the chance of design changes during construction and conflicts between stakeholders. Also, the end users of the facility can be trained on the acquaintance of the facility and evacuation procedures during emergencies.
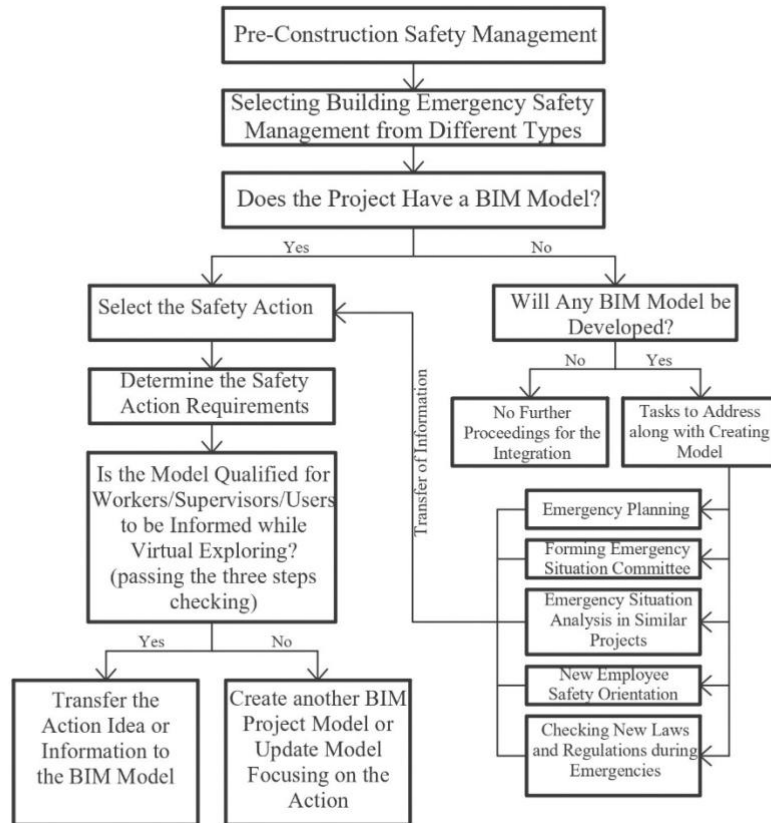

Figure 3: Flowchart of module 2 for generating information from the pre-construction safety management aspect, checking the BIM model's eligibility, and transferring information to the BIM model.

Next, in module 2 (shown in Figure 3), the first task is determining whether the project's BIM model has been developed. If completed, it should be decided which safety action will be incorporated into the BIM model. For case study 2 of this paper, evacuation modeling is selected to demonstrate the capabilities of the proposed framework. In contrast, if the project BIM model is not created, it should be determined whether any BIM model will be developed for the project. However, if the BIM model creation is in progress, there are some safety tasks that should be worked on in the meantime, and the task information can be transferred to the safety action determination process. These functions can also be addressed after the BIM model's development and during the selection of emergency safety action tasks. The functions are 1) Emergency planning, 2) Forming an emergency situation committee, 3) Emergency situation analysis in similar projects, 4) New employee safety orientation, and 5) Checking new laws and regulations during emergencies.

After selecting the specific safety action, identifying the model element requirements of taking the action is essential. For case study 2, the model elements requirements come from several research papers discussed in the literature review. After determining the requirements, the project BIM model needs to be assessed based on three steps of checking described in Module 1. If the BIM model passes, the safety action information can be transferred to the model for further integration.

3.4 Utilizing BIM and 3D modeling tools

The idea and information transition from two safety aspects can be incorporated into the BIM tool, Revit (shown in Figure 1). At the same time, Revit, the 3D modeling tool SketchUp, can be used as supporting modeling software. The use of SketchUp is optional and depends on the characteristics and complexity of the construction site model, as well as the safety idea and information. For example, suppose some elements are required for specific

safety training or actions that are more complicated to design in BIM tools. Those can be created with other 3D modeling software and incorporated into the BIM model.

From the construction safety training aspect, the BIM model can be developed according to the training need, or the information and ideas can be incorporated with the previously built BIM model if they are satisfied. On the other hand, safety information and ideas from the pre-construction safety management aspect should be incorporated with the actual project BIM model developed BIM tools. This can be any infrastructural or construction site model required to satisfy the needs. Also, specific phase BIM models can be created for these two safety aspects but should resemble the actual project or construction site.

3.5 Transition tools

In this framework (Figure 1), as the transition tool, 3ds Max is shown. Using the tool before importing BIM models (developed by Revit) to the game engine Unity directly has some benefits. The way the two BIM tools export the .fbx file is not fully readable by Unity. Also, proprietary file formats such as .rvt, .skp, etc., cannot be directly imported into it. Some extensions would solve the issues, but these are more complicated, and there is a possibility of losing BIM data. Thus, 3ds Max is used as a transition tool for models created by Revit.

3.6 Game engines and character modeling tools/sources

Previously, the developed framework for the case studies illustrated how BIM models from different tools could be imported into Unity. However, a template is needed before importing the models, and Unity offers some built-in templates. After selecting a template, BIM models need to be imported as assets. Not only BIM models but any external object that is also added or imported to Unity is called an asset, and inside the scene tab, the objects are called game objects. Some basic tasks must be done following the safety simulation tasks requirements after importing the model (shown in Figure 1) to Unity. The first task is configuring an architectural visualization scene. This includes optimizing meshes by generating lightmap UV for best quality lighting, removing sharp edges of a component, converting texture assets to normal maps, etc. The configuration can be altered according to the requirements for the construction safety simulation. The second task is scene design, which includes many activities. These activities depend on the end user requirements and how the scene fulfills safety ideas and information requirements.

However, some essential activities are working with prefabs, camera setup, adding additional objects or elements, generating collision data, configuring skyboxes, and optimizing camera render. In Unity, laws of physics can be applied to every object in the model. It is good practice to apply the rules, such as gravity and force laws, to the model elements so they can be more realistic. Moreover, colliders are essential elements to use in Unity, and regarding physical collisions, collider components specify how an object should be shaped (Unity, 2017). Different types of colliders are crucial to use, especially on the model floors, walls, and other objects, so whenever the player explores virtually in the model, they cannot pass through the elements.

Assigning the model's materials and lighting is another crucial Unity task. If there are no problems with BIM data transfer, the materials and textures are typically imported together with the model. However, it is required to assign indoor lights inside Unity. Here, the reflection probe feature has the potential to improve lighting quality. Also, additional animated human figures are needed for safety simulation purposes, such as creating disaster scenes in construction, visualizing safe working practices, etc. In this situation, character-modeling software, such as Mixamo and Blender, might be suitable for designing and animating unique characters. Additionally, Unity has an asset store where various characters are offered in free or paid editions.

Adding interactivity is one of the most critical portions of construction safety simulation in Unity. C# coding adds interactivity, and the script file (.cs) must be attached to the game objects. Any script-writing platform, such as MonoDevelop, Visual Studio, etc., can be used to write scripts. With this C# coding, first, second, and third-person exploration, area-based interactivity, AR, VR, etc., can be done. After completing all the tasks and safety simulation, the game needs to be checked in the game tab. In the framework (Figure 1), both Windows and Mac OS are shown as the end-built platforms. The first reason to present these two platforms is to make the framework comprehensive, which can be utilized by most construction companies or professionals. The second and perhaps most crucial reason is to see whether or not the final games in the two case studies function similarly on these two platforms and to identify any discrepancies. After creating the game, the built file can be sent to construction safety professionals and workers to fulfill the purpose.

4. CASE STUDY 1

A case study on a real-life scaffolding failure accident simulation was conducted following the developed framework. The purpose of the simulation was to show the workers the common scaffolding accidents and train them to prevent similar incidents on a construction site. Thus, construction safety module 1 was utilized in the framework to generate and transfer safety training ideas and information to a BIM model to integrate that with the game engine Unity later. For this simulation, an under-construction building was required, where the scaffolding components could be added. Therefore, an under-construction BIM model was developed to represent scaffolding components and simulate a scaffolding failure accident. Any imaginary under-construction building could have been developed; however, as this case study aimed to simulate a real accident, a real scaffolding accident scene video from online was used to support the case study. Therefore, the requirements of the simulation and training came from it. In Figure 4, three screenshots of the accident scene video are shown collectively. The first image depicts four workers pouring concrete on the top slab of an under-construction building without having any PPE. The second and third images illustrate how the bottom support breaks, the scaffolding fails, and one of the workers falls from there.
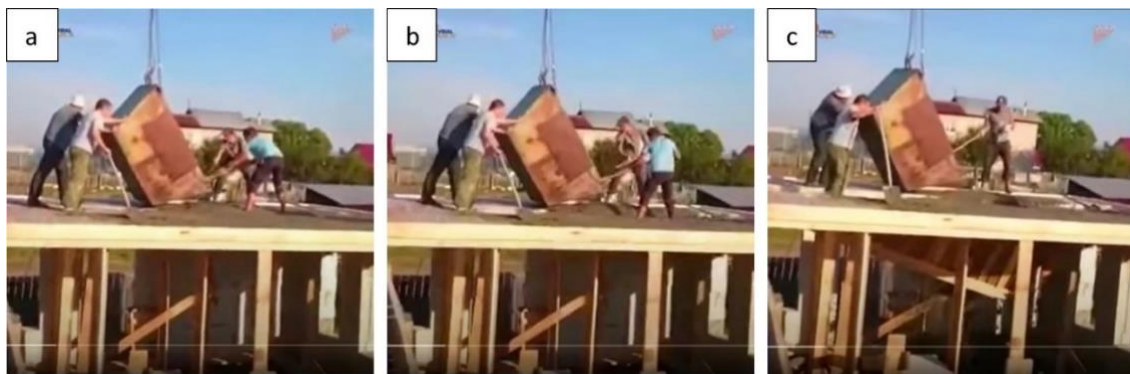

Figure 4: Real scaffolding accident scene from an online video: (a) concrete pouring on the slab; (b) bottom support failure and one worker about to fall; (c) scaffolding is wholly failed, and the worker is falling to the bottom floor.

Revit was used to develop the under-construction building model, according to the video (Figure 5(a).). Then, the model was checked for competency to incorporate additional features for simulating the accident scene. For this accident scene simulation, additional model objects or elements were required, such as cranes, concrete and buckets, scaffolding, and other components. These objects or elements were imported from 3D Warehouse and designed in SketchUp, and then the .skp file was transferred to Revit to incorporate those with the pre-built, under-construction building. Before finalizing the model, it was ensured that the elements that would be animated in Unity were individually grouped. Also, prefabs were used for scaffolding components so better optimization could be achieved.
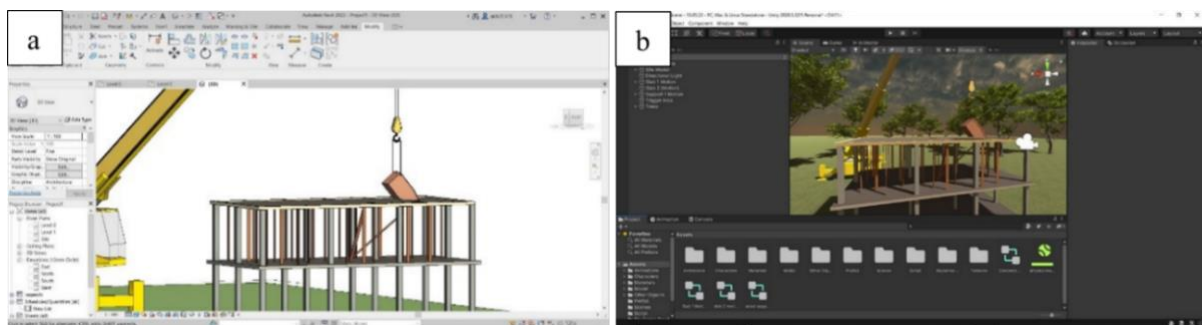

Figure 5: (a) The under-construction BIM model that was created in Revit; (b) the BIM model imported in Unity with adding Skybox and environmental elements.

After completing the BIM model, it was linked to 3ds Max, and later, the .3ds file was imported into Unity. Moreover, to find the effectiveness and efficiency of another path to avoid this mediator tool, 3ds Max, the final

BIM model was transferred to SkecthUp and then imported in Unity with two formats: .fbx and .dae. Before importing the file into the game engine, some additional tasks, such as creating a 3D HDRP template, asset folders, etc., were done. As the accident scene simulation would be conducted outdoors, no additional lighting was added to the model. Skybox settings were changed, and a High Dynamic Range Image (HDRI) and some trees were added to create an eye-pleasing environment. The result of importing the BIM model in Unity and adding the settings and elements is visible in Figure 5(b).

Mixamo 3D character animated software was used to add human characters to this model. Four characters with motion animation similar to the original accident scene were selected and exported as .fbx files. Then, the files were imported into Unity and positioned correctly.
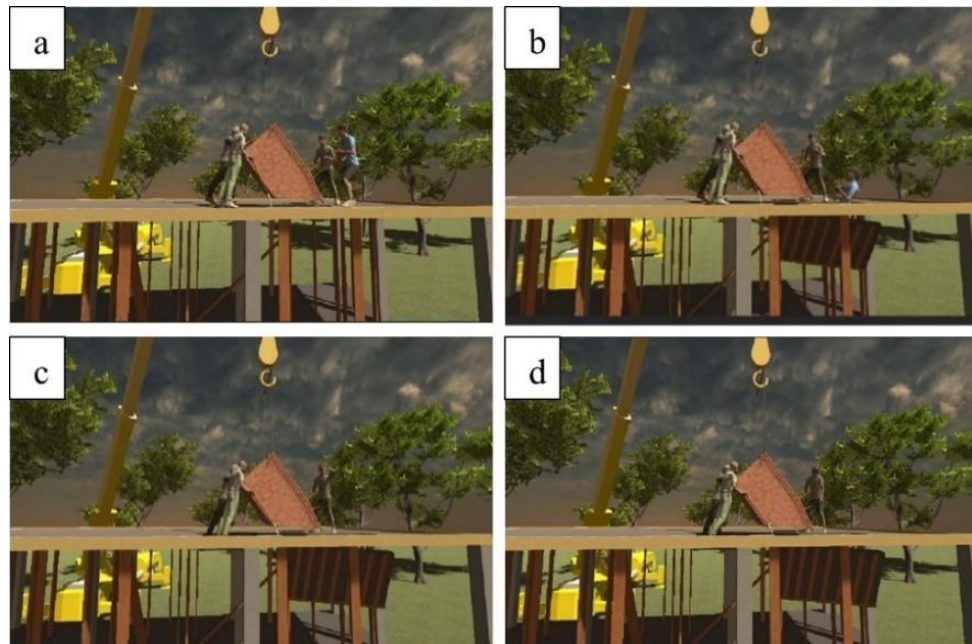

Figure 6: Animation and simulation of the scaffolding accident scene: (a) the workers working on concrete pouring; (b) the bottom support and scaffolding fail and one worker falling; (c) and (d) the other workers watching the falling of the victim.

In addition, all other animations were done inside Unity, such as scaffolding failure, slab twisting, failure of formwork support, character falling, and movement of concrete containing bucket.Sequencing all the animated clips was necessary, so those were arranged in the animator tab. Some triggers were also set by using C# coding. The Visual Studio platform was used, and the .cs files were attached to all relevant objects. Moreover, the primary camera was set in a convenient position so the whole accident scene could be adequately experienced. The simulation was tested in the game tab to troubleshoot any potential issues before validation. In Figure 6, four images of the initial animation and simulation are shown from the primary camera.
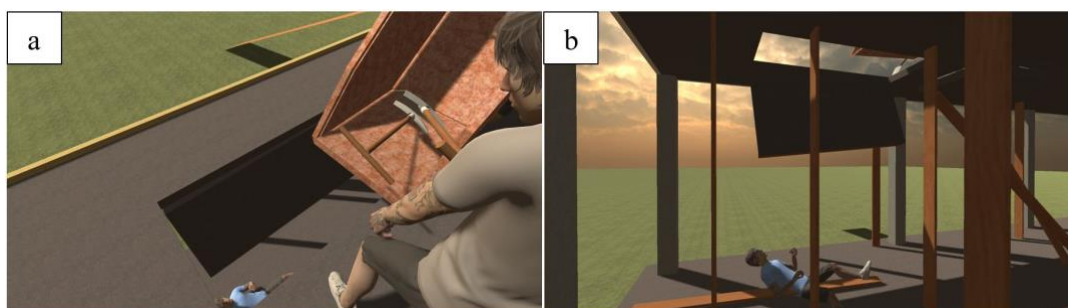

Figure 7: First-person view while experiencing the scaffolding accident simulation: (a) the workers fell from the roof; (b) the scaffolding failed as a result of inadequate and uneven support arrangement.

Following the simulation's first testing, the main camera was taken out, and another camera was mounted on the player object's head. It was also given appropriate C# coding to allow for movement. Therefore, the player or user could explore the whole construction site virtually with a first-person view. Starting from the beginning of the game and visible from various angles, the four workmen were pouring concrete from the bucket and placing it on the top slab. A trigger was set around the workers; therefore, the accident scene started to be simulated when the player came near the workers. It is possible to go near the workers from any direction; therefore, the player could experience the simulation from the desired angle. Moreover, the same simulation trigger was set at the bottom floor where one worker fell; hence, the simulation can be seen from the bottom view. The player could see how the accident happened and could explore the whole accident area.

5. CASE STUDY 2

Case study 2 was conducted on pre-construction safety management, specifically building emergency safety management, following the developed framework utilizing different BIM data transition pathways. Here, construction safety module 2 was used to generate ideas and information on a safety action and requirements, check the project BIM model's appropriateness for the action, and transfer information to the model. A real project BIM model was used in the case study, and it was a one-storied mental health and detoxification facility building model. The gross building area was 14,409 square feet, which is a large facility. The floor plan and the 3D view are shown in Figure 8.

The model was fully developed and ready to incorporate emergency safety actions after importing several components, e.g., a fire extinguisher from Autodesk library. Therefore, evacuation modeling was selected from the literature review as a safety action. The main idea behind choosing this safety action was to create an evacuation path to the exits so that the users could quickly move out of this facility from a certain region during emergencies. Also, this safety action can serve as a valuable information and training platform for the end users in the project turnover and operation phase. In addition, this modeling can help determine if there are enough exits for the facility before the construction begins. Moreover, the requirements for evacuation modeling, such as finding the shortest path determination from a specific point of the facility, area labeling, emergency equipment requirements, information regarding emergency equipment and exits, etc., were analyzed for the facility.

Figure 8: New mental health and detoxification facility BIM model; (a) floor plan; (b) 3D model.

The BIM model was primarily modeled in Revit, so the evacuation modeling idea and information were directly transferred here. However, the BIM model in Revit assessed the shortest evacuation routes for specific regions. The floor area of the model was large, and six exits were available. Some exits were the shortest for some locations, and those exits can be used for emergency evacuation for these areas only. After assessing the evacuation routes, the BIM model was exported as a .fbx file and imported in 3ds Max to avoid material and texture issues. In 3ds Max, extraneous model components and unnecessary layers were removed. In addition, the texture and materials were checked to see if they were correctly applied and on the proper scale. Then, the model was exported as a .dae file.

Both the .fbx file exported from Revit and the .dae file exported from 3ds Max were imported to Unity as assets. While selecting the models in an asset folder, it was found in the inspector ribbon that no materials and textures were embedded with the .fbx file; however, all materials were perfectly embedded with the .dae file. Next, the BIM model as a .dae file was taken into the scene tab in Unity and checked to assess if the model was on a correct scale. In this case, the model was not in the correct scale, so it was corrected by taking a cube model object (1m x

1m x 1m) in the scene and scaling it with the model. After that, a mesh collider was added to all the model elements, and the obstacles were defined. As a result, the player would not be able to move through the obstacles and would find free space to move. After collider systems were used in the model, a player was added to the scene for first-person exploration, and a camera was attached to the player's head. The materials and textures were embedded with the BIM model, so nothing had to change in the model. However, a new opaque material with some emission inputs was created for indoor lighting. The material replaced the core ceiling light fixtures material, and the changes were visible instantly. Then, the reflection probe game object was placed in a particular region where the player would explore the area. Then, the area was baked a couple of times, and finally, Unity calculated lighting.

When the lighting condition improved, it was required to create emergency evacuation routes. The best routes in the BIM model were assessed previously, and one way for one specific region was considered for development inside Unity. The course was shown by displaying an illuminated travel path created with the Cinemachine package's help. First, the package was installed in Unity from the package manager. In the Cinemachine package, the Cinemachine Smooth Path component object was added to the scene to create waypoints. The waypoints were customized to their position to make directions to the exits. After completing all waypoints, the route to the exits was indicated; however, this path was not visible in the game tab while exploring the area. As a result, a line renderer component was added to the object responsible for drawing lines. A C# script file from MonoDevelop was used to add all the points of the built trail. The .cs file was added to the Cinemachine Smooth Path object, including changing the line renderer width to 0.2m. Moreover, a light green colored transparent material having low emission intensity was created and attached to the line renderer.

After creating the evacuation path for a specific location inside the BIM model, the player object was placed in a different region from where the exploring would be started in the game tab. Thus, when the player begins first-person exploration and reaches the specific location, a message will pop up on the screen informing the player that it is an emergency and the player must follow the green evacuation route to exit the facility. Moreover, when the player entered different areas, location information was shown in the upper left corner of the screen. In addition, a mini-map was created to let the player know about the player's real location inside the building. The mini-map was placed at the bottom right corner of the game tab, which would help in navigation. Furthermore, 3D location information was provided on the floor for a better understanding of the different areas of the building.

When the player gets near the fire extinguishers, they start blinking, and messages on the screen show, "Fire extinguisher is blinking. Use it if necessary". In addition, automated door-opening interaction was added to the model for smooth and realistic exploration. Some other C# scripts, animations, animator tab, and box colliders as triggers were used for these interactivities. The evacuation modeling and interactivities were finally tested in the game tab.
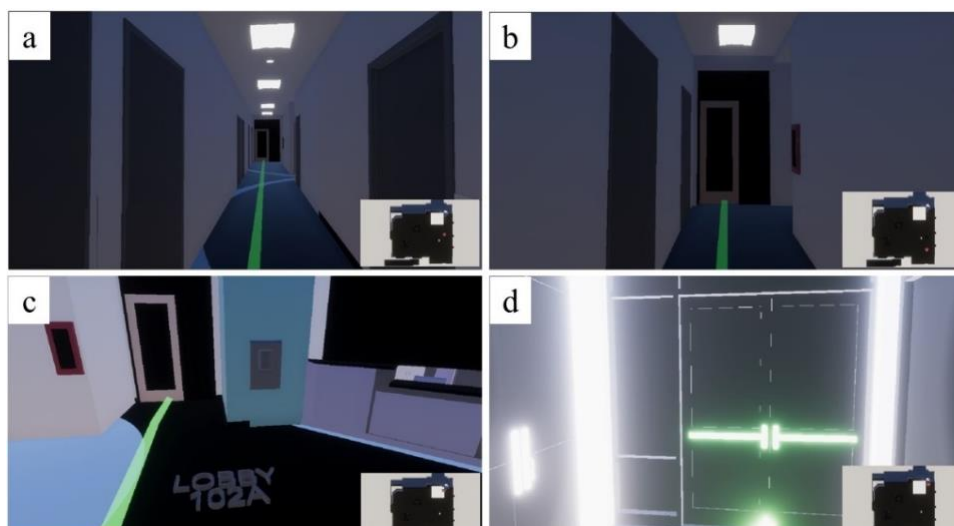

Figure 9: First-person exploration in the Unity game tab and the bottom right map showing the location of the user inside the building; (a) green line indicating evacuation path; (b) blinking fire extinguisher with safety instruction; (c) 3D location info on the floor; (d) illuminated exit point.

Figure 9 shows some images of the virtual exploration in the Unity game tab during emergencies, where the green illuminated line indicates the shortest path to evacuating the facility building (Figure 9(a)). The player can follow the path and exit the facility quickly, which will help the user remember the shortest path to take to exit during emergencies. Also, in Figure 9(b), a fire extinguisher blinks with a message in the top left corner of the screen as the player comes near the fire extinguisher. Moreover, 3D location information is depicted in Figure 9(c), which helps the player know the location of the enormous facility building. When the player reaches the exit point, the exit door starts blinking with white and green lights, including a top left corner message on the screen, letting the player know that it is the exit point and safe to be evacuated, as shown in Figure 9(d).

Finally, the game was built for both Windows and Mac OS platforms, and the application files worked accurately. This game can be used as a training platform for the end users to acquaint themselves with the inside facility, show directions of the shortest evacuation path from specific points, and provide necessary information on emergency equipment. Also, the BIM model's ability to pass the evacuation safety criteria for any emergency can be determined from the game simulation since users can leave the facility using any of the available exits within a set amount of time, regardless of where they are in the specified region.

6. VALIDATION OF THE SAFETY GAMES FROM THE CASE STUDIES

Table 1: Survey questions and answer types for validating the games from case studies 1 and 2.

Validation of the Game from Case Study 1		Validation of the Game from Case Study 2	
Question	Answer Type	Question	Answer Type
How do you rate the visual experience of the scaffolding accident scene from the online video?	Five options from completely ineffective to very effective	How difficult is reading the facility building plan and determining the best possible exit route to the outside?	Five options from extremely difficult to extremely easy
How do you rate the visual experience of the scaffolding accident simulation from the game?	Five options from completely ineffective to very effective	How difficult is finding the best possible exit route by virtual exploring inside the game?	Five options from extremely difficult to extremely easy
How accurately is the simulation done according to the online video?	Numerical scale from 0 to 10, where 0 means not accurate at all and 10 means extremely accurate	Can you remember the best possible exit route after finishing exploring inside the game?	Yes/no
Did you identify the root cause of the scaffolding accident from the online video?	Yes/no	Could you track your real-time location inside the facility building while doing virtual exploration?	Yes/no
Did you identify the root cause of the scaffolding accident from the simulation and virtual exploration?	Yes/no	Did you get information regarding emergency equipment, e.g., fire extinguishers, in different areas during virtual exploration?	Yes/no
If you find yourself on a construction site in the future, would your experience with this game help you prevent similar accidents?	Yes/no	Please rate the effectiveness of this game as the evacuation modeling and a training platform for the end users of the facility building.	Numerical scale from 0 to 10, where 0 means not effective at all and 10 means extremely effective
Is the virtual experience enjoyable compared to the traditional textbook/class learning experience?	Yes/no	Is the virtual experience enjoyable compared to the traditional textbook/class learning experience?	Yes/no
Is the safety learning experience facilitated by the game interactive?	Yes/no	Is the safe evacuation learning experience facilitated by the game interactive?	Yes/no
To what extent does the game stimulate your interest in learning?	Five options, from none at all to a great deal	To what extent does the game stimulate your interest in learning?	Five options, from none at all to a great deal
Do you find the game to be intuitive and simple to use?	Yes/no	How much do you recommend a game similar to this be implemented as a part of pre-construction safety management?	Numerical scale from 0 to 10, where 0 means not at all and 10 means a great deal

Twelve participants validated the safety games from two case studies. Of them, four had more than three years' experience, five had one to three years' experience, two had less than a year's experience, and one had no prior experience in the construction field. For the first game from case study 1, the online video of the real scaffolding accident was shown to them. After watching the online video, they played the scaffolding accident simulation game and explored the accident area virtually. After that, they completed a survey form with ten

questions/segments created by Qualtrics. After the participants had filled out the survey form, they were given the facility building plan used in case study 2. They were instructed to determine the best way out of the building in the event of an emergency using the plan from various locations. Next, the participants were provided with the emergency evacuation game, and they explored with first-person exploration. They completed an additional 10-question survey form after figuring out the fastest way out of the building from multiple points and receiving crucial information about emergency equipment and real-time location within the building. The questions from two survey forms are summarized in Table 1.

A few conditional logics were set in these two survey forms. The participants who responded 'Yes' to the questions 'Did you identify the root cause of the scaffolding accident from the online video?' and ' Did you identify the root cause of the scaffolding accident from the simulation and virtual exploration?' were further asked how difficult it was to identify the root cause of the accident for each question. The scale for the answer was from 0 to 10, where 0 meant not challenging at all, and ten meant extremely challenging. Moreover, the participants who responded 'Yes' to the question ' Could you track your real-time location inside the facility building while doing virtual exploration?' in the validation of the game from case study 2 were further asked, 'Which method of tracking your location in real-time is found the most convenient for you?'. Under the question, there were three options: mini-map at the bottom right corner of the screen, digital location information given at the top left corner of the screen, and 3D location information given on the floor of the facility building.

7. RESULTS AND DISCUSSION

7.1 Findings on the safety modules

The framework that was developed for the case studies was successfully implemented. The two safety modules of this framework were found effective in determining the specific safety actions and the requirements needed for the BIM models. Moreover, the eligibility checks were done properly for the BIM models based on the two safety modules. Therefore, the three 3D model eligibility checking criteria shown in this research can apply to any BIM model integrated with a game engine for construction safety management. It was found that the two modules were adaptable and ubiquitous in terms of pre-construction safety management and safety training requirements.

7.2 Findings on BIM data transitions and file formats

This study demonstrated two ways to link game engines with BIM data using two case studies. Although both paths were proven to be effective, there is a noticeable difference in their efficiency. In case study 1, an accurate model with perfect scale was produced, and no problems with the flow of data between Revit and SketchUp were identified. In addition, it was found that the components such as scaffolding, vertical and angular supports, and wires were hard and more time-consuming to model in the BIM tool than in the 3D modeling software. Hence, utilizing SketchUp to model additional components and transfer the files through .skp format was efficient. However, the whole modeling process took longer than the case study 2 modeling endeavor, where a real project BIM model was incorporated. Moreover, in case study 2, no additional modeling tool was used, and the required components were imported from the Autodesk library into Revit itself. It is intuitive to conclude that any pre-developed real project model is less time-consuming and more efficient to work on than building a model from scratch for integration with the game engine to enhance construction safety management. While importing BIM models in the transition tool, both .rvt and .fbx formats were found to be readable by 3ds Max as no 3D modeling information was lost. However, the proprietary .rvt file built a live link between the Revit and 3ds Max in case study 1, which was noticed advantageous over the .fbx format. The changes made in the Revit were reflected in the 3ds Max. A similar result was found when the model files were exported as .3ds (case study 1) and .dae (case study 2) from 3ds Max and imported into Unity. The live link was still alive for the .3ds file format; hence, any changes made either in Revit or 3ds Max were reflected in Unity. However, any changes done in Revit were not directly reflected in the game engine until the 3ds Max was opened and refreshed. Furthermore, common issues such as mapping errors and inaccurate scaling were not found while this transition occurred through the .3ds file format. However, in case study 2, the correct scale was not achieved when the 3D model was transferred via .dae file format from 3ds Max to Unity.

7.3 Findings on game engines in creating safety games

The Unity game engine was not meant to be a modeling tool in the case studies; however, it was found that components from different sources could easily be integrated with the scene if proper file formats were used. In

case study 1, it was found to be more efficient to incorporate human characters from character modeling tools/websites in .fbx format than modeling/importing them in the BIM tool. Moreover, it was observed that only the Skybox setting was sufficient for case Study 1, and no additional lights were required. However, for case study 2, lights were essential, and the player could not see clearly while exploring the facility without implementing lights. Also, it was found that the reflection probe feature played a vital role in lighting quality. It operated similarly to cameras that captured pictures of the scene from bygone vantage points, and the images it took were utilized to create reflections for smoothing objects. Higher lightmap resolution settings aided in enhancing the lighting's details. When textures were generated to contain lighting data, the lightmap size allowed them to modify their size. Higher pixel values, e.g., 2048 pixels, allowed for the inclusion of additional details but at the expense of excessive memory usage. Also, deactivating the compressed lightmap and activating ambient occlusion allowed better results in case study 2. For construction safety training and evacuation modeling, adding interactivity with C# coding was found crucial. Creating animation clips and utilizing the animator tab were perceived as essential for effective games for safety management. Moreover, with the C# script file, the animation's starting time was controlled, which was found important for construction safety simulation while the player explored the site in case study 2. Following the evacuation modeling and safety instruction testing in the game tab in Case Studies 1 and 2, the games were played on several machines after being developed for Windows and Mac OS platforms. No differences were found after building games on Windows and Mac OS, and the games ran smoothly on both platforms.

7.4 Validation results of the safety games

7.4.1 Scaffolding accident simulation game from case study 1

According to the responses of twelve participants, the visual experience of the scaffolding accident simulation from the game was much more effective than the online video. The result is shown in Figure 10.

Figure 10: Visual experience comparison of the scaffolding accident between the online video and game simulation.

The mean score was recorded at 8.58/10 on the developing accuracy of game simulation according to the real scaffolding accident scene from the online video. Moreover, 83% of respondents stated that they could not identify the root cause of the accident from the online video, whereas 17% indicated that it was moderately challenging to find the primary cause of the accident from the online video. However, all participants could identify the root cause of the scaffolding accident from the game, and it was not challenging at all, only slightly challenging on average. In addition, all the participants stated that this game would help them prevent similar accidents if they worked on the construction site. Additionally, the game was found fully enjoyable compared to the traditional textbook/class learning, and due to the interactivities, the game facilitated the learning experience. For two participants, the game developed their interest in learning a great deal; for nine participants, it was a lot, and for one participant, it was a moderate amount. Finally, every participant found the game to be intuitive and simple to use.

7.4.2 Emergency evacuation game from case study 2

Based on the survey result, finding the best possible exit route by virtual exploring inside the game was much easier than reading the traditional building plan and determining the quickest exit from different areas. The result of the difficulty rating is shown in Figure 11. Also, every respondent was able to remember the best possible exit route after finishing the game, and everyone tracked themselves inside the facility building virtually in real-time. Inside the game, there were three methods of tracking the player's location; among them, the respondents found the mini-map the most convenient. Moreover, each participant found vital information regarding emergency equipment from different areas in the virtual exploration. Therefore, the mean effectiveness rating of the game was recorded as 9.17/10, which indicated it was extremely effective as an evacuation model and a training platform for building occupants. Similar to the case study 1 game results, the participants reported that the game was far more interesting than typical textbook/class learning, and because of its interactivities, it made learning about evacuation easier. For five respondents, the game increased their interest in learning a great deal; for nine respondents, it was a lot.
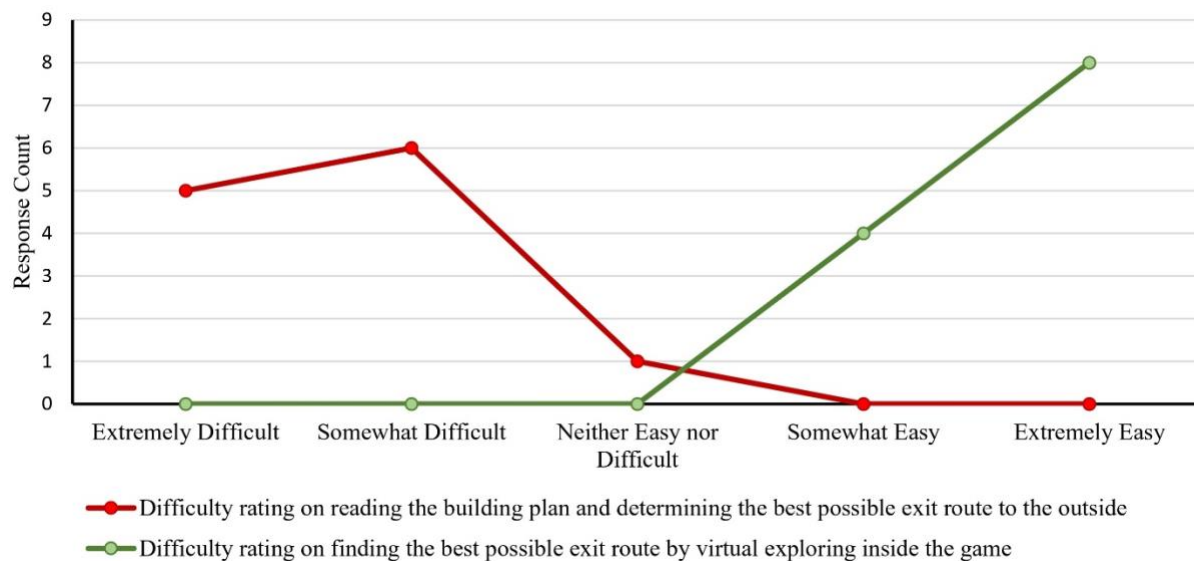

Figure 11: Difficulty rating comparison on finding the best possible exit route of the building between the traditional plan and the emergency evacuation game.

Hence, from the survey results, it can be concluded that game engines have the potential to improve construction safety management when integrated with the BIM data from real-life scenarios.

8. CONCLUSION

The construction industry is known for having high rates of accidents, including fatal ones. To improve safety, technology can be used to train workers and manage safety. Integrating BIM data and game engines can help with accident analysis, safety training, and pre-construction safety management. Two case studies were conducted to show the effectiveness of this integration, and two safety modules were developed to help ensure that BIM models are appropriate for specific safety training or action. Issues and recommendations for BIM data and game engine integration were also discussed, and the games were found to be effective in improving construction safety. Two case studies were conducted using a construction safety framework. The first study simulated a scaffolding accident to train workers to avoid similar incidents. The second study utilized the framework to create an evacuation path for a facility building project BIM model to enable swift evacuation during emergencies and provide end-users with information and training. The framework can also assist in determining whether a facility has enough exits before construction. For the first case study, safety module 1 was used to extract scaffolding accident training ideas and information to the BIM model. Additional components were imported in SketchUp and transferred to the Revit model using the .skp file format. The .rvt file was integrated with 3ds Max to create a live link. Then, the BIM model in .3ds file format was imported into Unity. Customized animations were added, and all coding was done using Visual Studio. For the second case study, safety module 2 was used for evacuation modeling. The BIM model was imported in 3ds Max through .fbx file format and integrated with Unity. An

evacuation path was created utilizing the Cinemachine package. Two safety modules of this framework help to identify safety measures and specifications required for BIM models. Using BIM models coupled with game engines for construction safety management is productive and less time-consuming. It is recommended that mediators or transition tools be used instead of importing BIM models into Unity directly. Live linkages between tools and game engines can be created using .rvt and.3ds file formats. Importing characters from character modeling sources via .fbx file types is recommended. Participants played both games and filled out two separate survey forms to validate the effectiveness of improving construction safety management in the real field. The scaffolding accident simulation game's visual representation was found to be more effective than the online video, and the evacuation modeling game was simpler in determining the best feasible escape route. Both games were highly effective and recommended for construction management safety improvement. In conclusion, the two case studies shown in this paper can be used as guidelines for safety professionals to build games for similar training and safety actions for construction projects. Moreover, further research can be conducted utilizing the developed framework of the case studies. Thus, game engines and BIM data integration can have a significant impact on enhancing construction safety management. Safety measures and training can be carried out to lower the number of fatal and nonfatal accidents in construction projects with the help of integration.

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